MULTIDIMENSIONAL ANALYSIS OF THE ELECTROENCEPHALOGRAM USING DIGITAL SIGNAL PROCESSING TECHNIQUES

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THESIS

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by

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Multidimensional Analysis of the Electroencephalogram Using Digital Signal Processing Techniques

by

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ABSTRACT

The first series of results of a major research project for the analysis of the electroencephalogram (EEG) are reported.

The requirements of a system capable of real time, multidimensional analysis of the EEG are described. The time and frequency domain computer analysis programs written for the project are discussed.

A major result of the research indicates that a significant portion of the EEG is composed of a series of discrete frequency sinusoids. These signals have a spindle shape and their average durations are constant over the frequency range from 14 to 50 Hz, with the exception of sinusoids of 42 Hz. The signals are defined as tegules.

The properties of a tegule are defined, as found from experimental results.

The anomaly with respect to the 42 Hz tegule is related to the subject's mental state and may be a source of feedback to indicate whether he is thinking or relaxing.

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ACKNOWLEDGEMENT

It is my pleasure to acknowledge the members of the research team. The project size and mass of equipment required to pursue the project and the technical knowledge required to build and maintain the equipment far surpass the ability of a single man to achieve.

First on the list of acknowledgements is Professor George Marmont whose guidance and leadership were required from the conception of the project as an idea and will be required until the project is completed.

Second on the list is Erich Lauff, our lab technician. Erich has been especially valuable in construction of special electronic equipment for the project.

Professor Gary Garrettson of the Physics and Chemistry Department participated in the experiments until he left the school last September.

Other members of the team are some of the Bioengineering thesis students. These include LCDR Ron Jolley, LT Bill Stockslager and LT Ed Ohlert. These students helped in data acquisition and were invaluable as the primary subjects for the project.

A special acknowledgement must be given to the Naval Electronics System Command for their interest and continued support of the research project.

I. INTRODUCTION

A. BIOENGINEERING

The options available in the Electrical Engineering Department specified as Bioengineering courses afford the Electrical Engineer the opportunity to learn to relate his electronic background to problems concerned directly with man.

The study of human biology as related to engineering is quite natural since engineering is the application of devices for the use of man. Man has developed areas of knowledge such as engineering by the use of his brain. If he can then use engineering to make better use of his brain, the loop has been closed. Computer technology is an example where engineering has allowed man to make better use of his brain by freeing it from the necessity to perform tedious calculations. A knowledge of human biology enables the engineer to better apply modern technology for the benefit of man thus reducing the manpower required to achieve a specific result.

Man is the only ultimate weapon of any armed forces and the greatest natural resource of any country. The misuse or wasteful use of manpower cannot be tolerated if a nation is to be competitive in a modern world concerned with peace or war or both.

B. THE BIOENGINEERING TEAM RESEARCH PROJECT

Our knowledge of the biological aspects of the brain, while far from complete, has increased tremendously in the last few years. However, our knowledge of how the brain works is so incomplete as to preclude the use of most of the data readily available from the brain.

The brain is generally considered to be a device that operates on an electrochemical basis. Some of the electrical activity of the brain may be detected via electrodes on the skull.

The research project consists of the detection and analysis of these electrical signals (electroencephalogram). It is proposed that the electrical signals available from the brain contain information as to the type of processing the brain is performing and that the correct analysis of these signals will allow determination as to the effectiveness with which the brain is performing. One of the goals of the research project will be the feedback to a man of a signal indicative of the effectiveness of his brain processes for the purpose of modifying these processes towards a more correct and efficient solution to a problem. The project is expected to encompass several years.

NAVELEX has considered this project so important as to fund it over the last two years. The project is far too complex and expensive to have been possible without the support of NAVELEX.

It should be obvious that a research project of this magnitude and duration requires the talents of many people and hence the team aspect of the project.

C. THE AUTHOR'S CONTRIBUTIONS

The author has been a part of the project since its inception and has participated in planning of the project, writing of equipment specifications, purchasing of equipment, debugging of equipment and the development of specialized devices such as high gain, low noise I. C. preamplifiers.

A significant portion of the computer programming effort outlined in Section IV and the experiments and data analysis presented in Section V and Section VI are the specific contributions of the author.

The thesis describes the project objectives and the carrying out of the team project. The analysis of the results and their interpretation is the responsibility of the author.

II. BACKGROUND

A. THE ELECTROENCEPHALOGRAM

The initial enquiry into the electrical activity of the brain was restricted to experimentation with animals. As early as 1875 Richard Caton [Ref. 1] discovered a small current flow existed between two electrodes attached to the skull of an animal or between one electrode on the skull and one on the grey matter. In these early experiments the detection of the electroencephalogram (EEG) was accomplished by use of galvanometers with optical magnification and permanent records were made by photographing the deflection of the light beams or by manual recording of the readings.

The first EEG of a human was recorded in 1929 by Hans Berger. He used various types of electrodes including platinum wires stuck into the scalp, zinc plated steel needles and large plate electrodes [Ref. 1].

The advent of the vacuum tube amplifier and the cathode ray tube facilitated the study of the EEG. The differential amplifier became available somewhat later and improved the quality of the EEG by elimination of the common mode interference signals. Since the 1950's, techniques and technology have improved significantly.

The major recent advance in the study of the EEG has been the application of computer processing techniques. With today's increasing computing speeds, hardwired peripherals such as DFT boxes and drastically reduced costs, computer aided analysis of the EEG is not only practical but absolutely necessary if man is to ever understand the single most complex and intriguing system on earth; i.e., the human brain.

B. USAGE OF THE EEG

1. Diagnosis of Epilepsy Type

Epilepsy has two primary forms; that involving the entire central nervous system, called generalized epilepsy [Ref. 2] and that limited to a particular small area of the nervous system and known as partial epilepsy.

The specific types of epilepsy are diagnosed by particular frequencies and patterns in the EEG and by the areas of the central nervous system involved.

2. Detection and Approximate Localization of Tumors

A brain tumor generally results in an excessively excited neuronal discharge at the location of the tumor. Placing a large number of electrodes on the scalp and observing the results can lead to the general localization of the tumor by noting those electrodes showing typical tumor EEG; i.e. EEG contaminated with large spikes [Ref. 2].

3. Detection of Brain Death

A flat EEG is even becoming the criteria for determination of death [Ref. 3].

4. Monitoring the Depth of Anesthesia

The depth of anesthesia is characterized by specific EEG signatures, and is therefore monitored during certain types of operations [Ref. 4].

5. Evoked Response

The evoked EEG response is obtained by presenting a repetitive stimulus to a subject. The response is waveform averaged and tends to give a characteristic waveform depending on the type of stimulus and the condition of the subject. For example, the visual evoked response is being successfully used in optometry. A repetitive flashing pattern is

presented which a subject views through lenses of a series of diopters. The proper corrective lens will allow the production of a maximal visual evoked response which also has characteristic signature features [Ref. 5].

C. CHARACTERISTICS OF THE EEG

1. Electrical Characteristics

The EEG detectable on the surface of the scalp rarely exceeds 100 μv amplitude and is normally about 50 μv. The method of detection has some effect on the measured amplitude as it determines the reference to which the measurement is made. Unipolar measurement of the EEG is the differential measurement of two active electrodes one of which is commonly attached to an ear lobe or other non-scalp position while the other is attached to the desired area of the scalp. Bipolar measurement of the EEG is achieved by connecting the channels in series between electrode pairs.

The frequency content of the scalp EEG has been considered to be primarily below 50 Hz. The largest amplitude signals are normally found from D. C. to 12 Hz with a significantly smaller amplitude band ranging from about 12 Hz to about 30 Hz. Smaller amplitude signals can be found out to 50 Hz and beyond. It has been proposed that frequencies as high as one kilohertz are present in the scalp EEG and may be detected with the proper measurement techniques.

The scalp EEG may be contaminated with very large noise signals due to external signals and signals from the heart and muscular activity. The electrical signal from the heart is called the electrocardiogram (EKG) and may exceed 20 mv or more. The EKG can be effectively shielded from the head by connecting an electrode from the neck of the subject to the system ground. This, in effect, shields the head from all signals

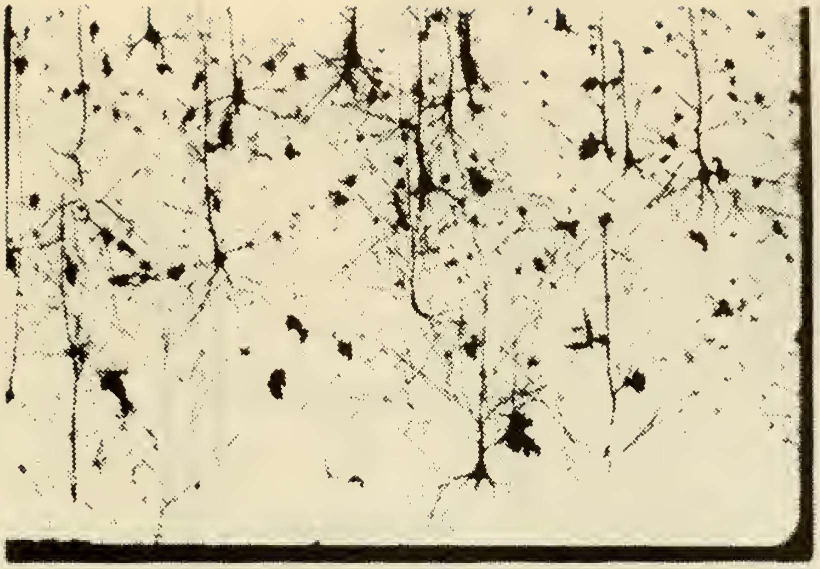
originating below the neck which includes the EKG. The electrical signals due to muscles other than the heart are termed electromyograms (EMG), and if they arise due to muscles on the head, they cannot be shielded from the EEG.

The most difficult signals to eliminate from the EEG are external environmental signals, of which the worst is 60 Hz. The 60 Hz on the head is likely to be orders of magnitude greater than the EEG signal. Since the 60 Hz signal is essentially the same at all points on the head, it is possible to eliminate by differential amplification. The magnitude of the 60 Hz component requires a common-mode rejection ratio (CMRR) of the amplifier of at least 90 db to achieve EEG's free of 60 Hz signals.

2. Individual Neurons

There are on the order of 10^{10} neurons in a human cerebral cortex, and each of these neurons can have hundreds of connections to other neurons giving an inconceivable number of possible interconnections. Figures 2-1a and 2-1b are examples of typical pyramidal nerve cells. The inputs to the neuron are via the axon branches of other neurons. The actual junction is via a synaptic junction shown in Figure 2-2. When a neuron fires, an action potential voltage is propagated via a local generation process down the axon. When the action potential reaches the synapse, a chemical transmitter is released and diffuses across the synaptic cleft. Depending on whether the input is excitatory or inhibitory, the chemical transmitter causes the receiving membrane potential to be decreased or increased respectively.

As the dendrite membrane potentials vary with the incoming signals, they fluctuate positive and negative with respect to the cell body



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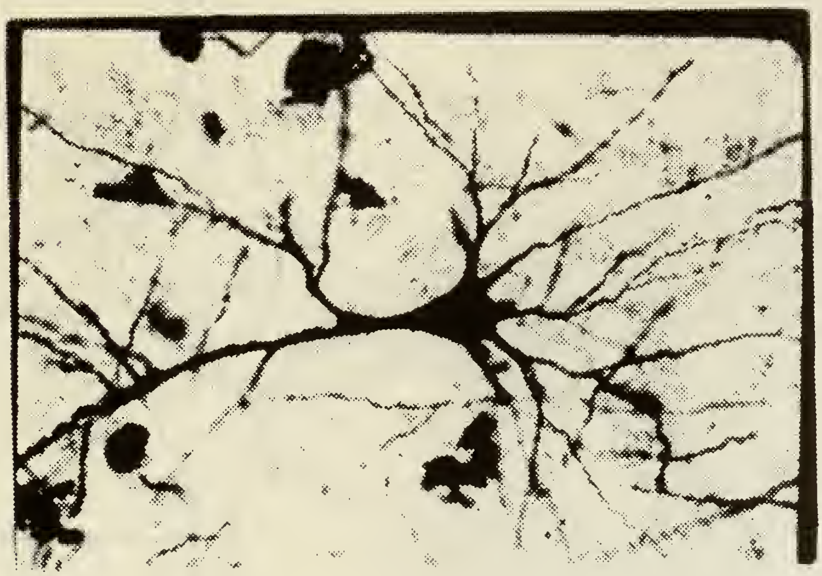


B

Figure 2-1. (A) Typical pyramidal cells found in the cortex; (B) A further magnification to show a single cell.

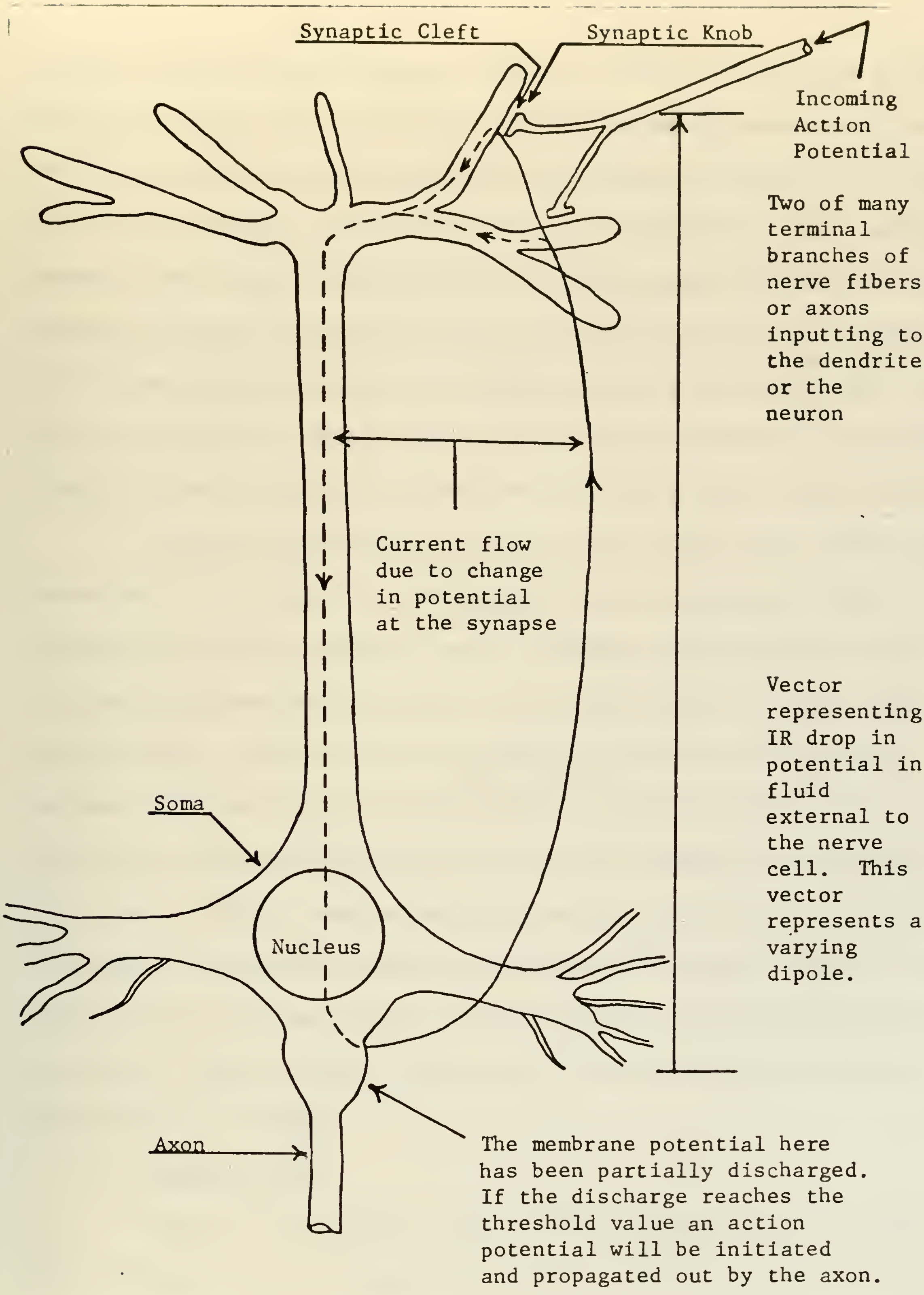


Figure 2-2. A simplified diagram of a neuron in the cortex such as a pyramidal cell.

or soma. This voltage difference causes a current to flow from the dendrite to the soma with one leg of the loop current flowing inside the dendrite process and the other flowing external to the neuron (see Fig. 2-2). The external current flow causes an IR drop in the surrounding medium. The average currents due to the many signals give rise to slowly varying voltage fluctuations in the vicinity of the neuron even though the incoming signal rate to the dendrite may be as much as 1 KHz. The rate of incoming action potential signals may vary with time. The fluctuating signals affect and in turn are affected by other nearby neurons.

If the incoming excitory signals should sufficiently lower the potential of the neuron to a threshold value, the neuron will fire and produce its own high-amplitude action potential. The action potential is then propagated down the axon of the neuron and is an input signal to other neurons. There is not necessarily a one to one correspondence between an incoming action potential to the nerve cell in question and an output action potential from the cell. For example, it may require the summed effect of many incoming action potentials before the threshold change in potential from the receiving cell has been reached. Indeed, if the neuron receives volleys of both exciting and inhibiting inputs no action potential might be setup but the soma membrane would merely fluctuate in potential.

3. Resultant EEG

There are two distinct types of EEG depending on what is measured. If a microelectrode is inserted into a neuron and the actual input signals are measured, the EEG will consist of high frequency components equalling 1 KHz in some instances. If on the other hand, an electrode is positioned in the medium surrounding a neuron, then a much lower

frequency EEG will be measured representing the average fluctuations of many neurons in the general vicinity of the electrode as described above. If the electrode is placed on the scalp of the subject, the EEG shows the resultant activity of many millions of neurons. The skull and other material between the neurons and the electrodes act as conductors which are, in effect, extensions of the electrodes. Thus a weighting factor is ascribed to the contributions of the neurons to the EEG depending primarily on the radial distance from the electrode to the particular neuron.

4. A Dipole Model of the Cerebral Cortex

For the purpose of considering how the EEG is established, the dipole model is instructive. If the reference electrode is connected to an ear lobe, it can be considered to be at the center of a volume conductor and the distributed neurons can be grouped under electrodes and considered to be oscillating dipoles oriented perpendicular to the surface (see Fig. 2-2). As the dipoles oscillate in magnitude and polarity, the associated electrodes will detect the varying radially directed potential gradients from their dipoles and, to a lesser degree, the gradients of the other dipoles.

D. EEG MEASUREMENT AND ANALYSIS METHODS

A preliminary question that must be considered proir to either measurement or analysis of the brain is how one can measure the output of the brain in an objective manner? The main obstacle to answering this question is that the operation of the brain is not at all well understood. It is generally established that the brain is a non-linear, stochastic, electrochemical device; therefore, it seems reasonable that the measurement of the electrical activity of the brain could be one effective measurement of brain activity.

1. Neuron Measurements

Methods employing the use of micro-electrodes have been developed to the point that the researcher can measure the electrical activity of small populations of neurons or even individual neurons. These measurements are most often done on animals but have been used on human subjects. The most obvious reason for not using this method in the current research project is the requirement of open skull surgery. Even if this difficulty could be overcome, there are definite disadvantages to discrete neuron measurements.

A neuron is a highly non-linear device and present knowledge does not allow one to predict the behavior of as small a population as twenty neurons even though the individual neuronal inputs are known. One is forced to the conclusion that the way to study the electrical activity of the brain in a problem-solving environment is to use statistical analysis techniques applied to very large populations of neurons. The measurement and stimulation of small groups of neurons have contributed a great deal to our understanding of the brain. For example, most of our knowledge of the functional locations on the brain are due to the stimulation of neuron groups (see Fig. 2-3). Single cell measurements have established the action potential, cell firing rates, etc. [Refs. 6 and 7].

2. Evoked Responses

The evoked response is the resultant EEG after application of a known stimulus. The most common types are the evoked visual response (EVR) and the evoked auditory response (EAR). The ER came about as an attempt to relate the EEG to a known event occuring at a specific time. This is in recognition of the extreme complexity of the EEG whether the subject is engaged in a specific mental task or is in a supposed relaxed

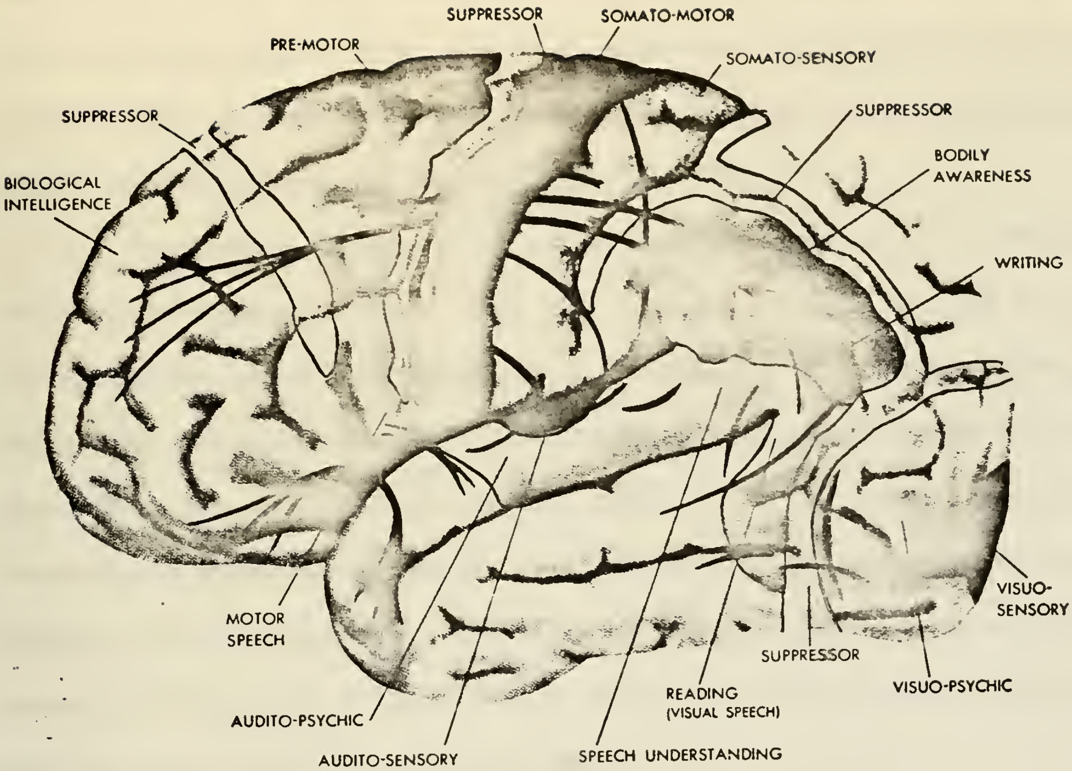


Figure 2-3. The cerebral cortex. Localization of function and association pathways. (From The Ciba Collection of Medical Illustrations, Volume 1, "The Nervous System, by Frank H. Netter, M.D.)

state. Even in a relaxed state, the brain must still maintain the proper heart rate, blood pressure, breathing rate, temperatures, CO_2 concentrations, etc., etc. Thus the brain is in a continual state of multivariable change due to the many parameters of the body that it must control and the many continuously changing sensory inputs and the processes involved in neural processing.

In order to separate out an ER from the complexity of the EEG, waveform averaging is used. Here the stimulus trigger is used to initiate the epoch over which each waveform is averaged. If a large number of epochs are averaged, the EEG not attributable to the stimulus will average toward zero and only the ER will remain. It may be desirable to present the stimulus at random intervals to prevent an anticipation response from the subject. The number of epochs required to obtain a repeatable ER varies from as few as twenty for some types of EVR to as many as one thousand for certain EARs.

The ER is at best a measure of the response to a given stimulus with no part of a 'thinking' process included. This argument stems from consideration of the environment of the subject and the type of stimulus. Consider an EVR situation in which the stimulus is a flashed light. During the first few stimulus presentations the subject may consider the source of the light, its color, the trigger mechanism, etc. Certainly the subject's thoughts about the light will vary during different epochs. Thus, the use of waveform averaging to suppress the EEG not synchronized to the stimulus will also average out any EEG related to 'thinking' about the stimulus. That is, the subject's thought variation from stimulus to stimulus will cause those thoughts to behave as noise and average toward zero. At worst the ER can be completely without meaning. For example, if the experimenter is not careful he may use such a large stimulus as

to cause the subject to flinch or to cause some other muscle action. The myogram response is generally at least an order of magnitude greater than the EEG and will mask the EEG.

Although the ER has some value as a tool for indicating proper operation of the sensory input systems, it is felt that it has very little, if any usefulness as an aid to understanding those brain processes referred to as thinking.

3. On-Going EEG

The on-going EEG is typically obtained by simply amplifying the EEG to a useable level and recording the results on a strip chart recorder. The amplifier is usually RC coupled with about a 0.5 Hz or higher, low frequency cutoff. Sixty Hertz interference is a normal problem which is alleviated by a 60Hz notch filter or by simply limiting the high frequency response to considerably less than 60 Hz. The difficulty in analysis of complex time domain records has been attested to throughout the available literature [Refs. 8 and 9].

The necessity for sophisticated means of analysis of the EEG is obvious. Many attempts have been made to use computers to analyse the EEG,and those range from simple integrations or zero crossings techniques [Refs. 3 and 9] to sophisticated differential equations and curve fitting techniques [Ref. 10]. The zero crossing technique counts the number of zero crossings within a given time period and calculates the frequency based on the time intervals. This technique is not very good. Although it works fine for a single frequency waveform, it may be completely erroneous for a multi-frequency signal and is obviously ridiculous if applied to the simple case of a square wave.

Other attempts at analysing the EEG include automatic pattern recognition of sleep stages [Ref. 9], special graphic spectral analysis

displays [Ref. 8] and an interesting computer program for the computation of conditional probabilities of substrings of data [Ref. 11]. The vast majority of analysis techniques have two things in common; they rely exclusively on spectral analysis and are processed off line with associated long time delays between the taking of data and the resultant analysis. Usually the data is output in a printed tabular form. This is an inconvenient means of hard copy for data storage and interpretation.

III. RESEARCH OBJECTIVES

The research objectives were to apply modern signal processing techniques and methods of analysis to the EEG with the following principal expected results:

(1) New insight into the meaning of the EEG as an expression of brain function.

(2) New knowledge that could be applied for such purposes as improvement in training methods, reinforcement of an individual while he is engaged in a demanding mental task and detection of mental states such as incipient fatigue.

A. MEANING OF THE EEG

The EEG as recorded from a single scalp electrode represents the sum of activities of millions of neurons directly beneath the electrode and is influenced somewhat by all the other neurons within the brain. The question arises as to whether it is an orderly expression of brain activity. The evidence of repeatable ERs and the fact that the ER does change as a function of the input signal, the prominence of a rather constant frequency near 10 Hz from subject to subject, the change in the EEG as a subject's level of alertness varies, and the dramatic changes in the EEG when a subject opens or closes his eyes are just a few examples of phenomena that overwhelmingly support the thesis that the EEG is a valid expression of brain function.

B. REAL TIME, MULTIDIMENSIONAL ANALYSIS OF THE EEG

Real time analysis of the EEG is the means by which the basic premise of feedback reinforcement could be met. The considerations of the neuronal

delay times and general human response times led to the conclusion that positive feedback would require data update times to the subject within the range of 0.1 to 1.0 seconds.

The speed requirements in order to achieve 1.0 second or less feedback delay and the complexity of the EEG constrain the analysis system to be a 'state of the art' computing facility. The type of analysis that seems obvious is spectral analysis but a little reflection as to what spectral analysis is and why it appears to be an obvious choice will suggest other forms of analysis as well.

1. <u>Frequency Domain Analysis</u>

Spectral analysis is limited to a frequency resolution of 1/T where T is the time over which the discrete Fourier transform (DFT) is taken; therefore, a DFT taken over a time of 0.1 second limits the frequency resolution to 10 Hz. This would be totally unsatisfactory and even a time of 1.0 second results in a limiting resolutions of 1.0 Hz which was considered insufficient by the researchers. A reasonable solution is the sliding time window concept discussed in Section IV. Time limitations imposed by the update do not allow any form of tabular output formats, and only a display of frequency versus amplitude would allow an observer to assimilate a significant portion of the data. Further consideration indicates that the complex Fourier series would be an inappropriate data format for the observer due to the necessity to be cognizant of both the frequency and its phase as well as amplitude. The only viable formats are then either power spectrum, cross spectrum, or magnitude of the transform.

Stationarity is not considered to be a valid assumption for the EEG. This does not mean that the DFT is useless, it merely means that one

must be cautious in its use. A specific use of the Fourier series might be as a means of determining the average of the frequency components present in a particular time window.

2. Time Domain Analysis

Consider an analysis format that would retain the important advantage of spectral analysis, include the critical time variations and eliminate unnecessary complexity of data. This would seem to be an ideal format and can be achieved by digital filtering of the complex spectral components and reconstituting it into a time domain signal. The significant advantage of time domain is the ease with which one recognizes patterns as a function of time. A basic assumption on the operation of the brain assumes that it is a parallel processor; thus various areas of the brain would be expected to operate simultaneously on different aspects of the same task. The assumption would be supported if common patterns were found in signals from two or more areas. There are ways to enhance the ability of an observer to recognise patterns in the time domain. These are specifically auto- and cross-correlation techniques.

C. EFFECTIVE USE OF THE EEG

An objective of this project is to apply the engineering principle of feedback to the human brain in such a manner as to allow a subject to modify his performance in such a way as to improve his ability to solve a problem or to learn. A simple example will serve to illustrate the point. Without the ability to hear one's own voice, one would find it difficult to learn to talk,and,in fact, congentially deaf people are also dumb. On the other hand some radio telephone links have a delayed echo, and with a fraction of a second delay, people find it difficult and in some cases impossible to talk. Thus feedback can enhance the ability to learn a skill but the timing must be right.

1. Use of Feedback of the EEG in Training

For the purposes of this paper, the act of training will be defined as the teaching of a pattern recognition and response technique. This definition covers essentially every operator task in the Navy in which the man is operating a piece of detection equipment such as radar, sonar, ECM, etc.

The use of feedback of the EEG in the training of operators presupposes that there exists more than one way for the brain to process the information supplied by the detection equipment and that the EEG varies with the processing method. The background illumination of a piece of detection equipment could be keyed to the student's EEG. If one particular pattern of EEG indicated an optimal approach to the correct identification of the target, then the occurence of the color corresponding to that pattern would serve to cue the student that he is on the right track. The student would then teach himself the best processing technique to use (which might be expected to vary from student to student) for the specific task at hand. Thus by feedback reinforcement the learning process could be facilitated. It should be noted that this would be very similar to the method by which a child learns to speak.

2. Operational Usage of the EEG

Similar techniques could be used in an operational environment. The advantage would be the reduced time required for an operator to make a decision with regard to the presence or absence of particular targets. Here time is of the essence. Examples might be the prosecution of a submarine in an ASW environment or a successful kill in an aircraft to aircraft combat situation.

Most aircraft losses in a cold war environment are known to be a result of pilot error. The modern military aircraft is approaching a

cost per airplane of twenty million dollars and no figure can account for the loss of human lives. The modern aircraft now has a 'heads-up display' (HUD) which allows the pilot to display the status of his aircraft as symbols that appear to originate at infinity and are observed through the windshield of the aircraft. The HUD would be an ideal vehicle to present the processed EEG to the pilot so that he would be aware of his mental state. Thus, the pilot would be warned of incipient fatigue or inattention in a positive manner.

IV. METHODS

This section describes the methods used in the research program. These methods include the selection and tasking of the subject and the leading off and processing of the EEG's. Figure 4-1 shows the overall experimental set up.

A. SUBJECTS

The subjects used were all volunteer students of the Naval Postgraduate School or members of the research team. No specific traits or talents were required of the subjects.

1. Environment

The subjects were seated inside a standard copper screen room. The prime purpose of the screen room was to provide enough isolation so that the subject would be able to concentrate on given tasks without undue disturbances from outside. It also may serve to diminish ESP. The screen room was furnished with a comfortable padded chair that was capable of continuous positioning from full upright to full recline. The use of the reclining chair allowed the subject to fully relax physically when only mental tasking was required.

A second chair was available for use in experiments that required the subject to recognize patterns. The patterns were sonograms which displayed frequency as the abscissa versus time as the ordinate on a strip chart type of record. The amplitude of a signal was indicated by line darkness and width. Actual grams that had been obtained from sonobuoys placed in the ocean were used. If a ship or submarine were near the sonobuoy, the acoustic signals emitted by the target would be detected

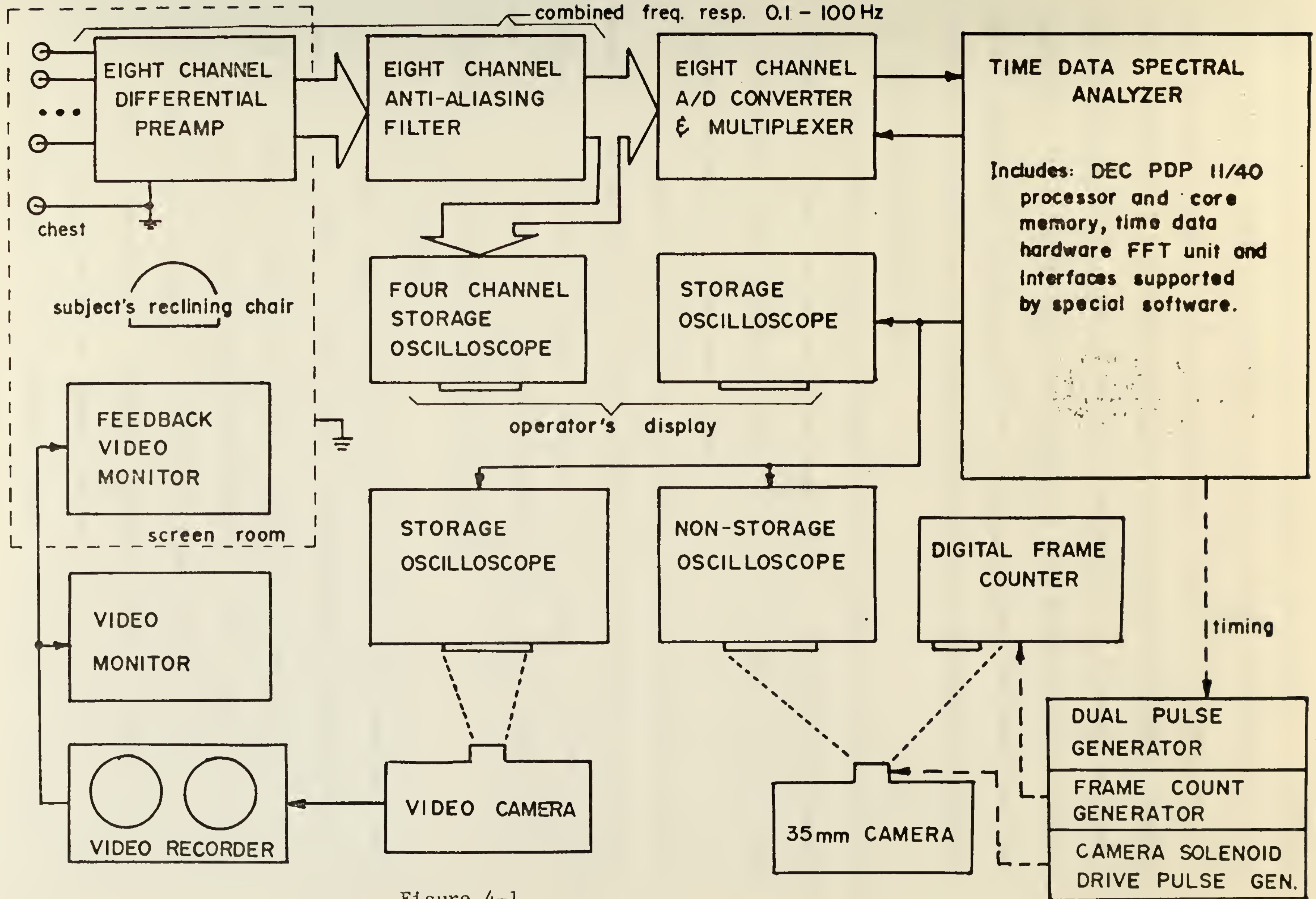


Figure 4-1.
BLOCK DIAGRAM OF DATA ACQUISITION, DATA PROCESSING AND OUTPUT DISPLAY SYSTEMS

by the hydrophone of the sonobuoy and relayed to an aircraft. Equipment in the aircraft (AQA-7 equipment) would then record and display the signals received. A given target classification comprises a unique set of basic frequencies, harmonics and order of prominence of harmonics associated with shaft rate, number of blades, engine RPM, turbines, auxilary equipment, etc. The problem of recognition of a specific target signature becomes quite complex since the range of a base frequency can vary. Ocean conditions affect the number and order of prominence of harmonics and multiple targets can occur.

Great care was taken to ensure that the subject was as comfortable as possible during the course of the experiments. Any physical discomfort of the subject could adversely affect the EEG and prevent him from devoting full attention to the task at hand.

The screen room contained a television monitor that was used to provide live feedback to the subject and for presenting some of the experiments that were previously recorded on video tape. An AQA-7 simulator was available in the room to display grams to the subject when pattern recognition experiments were being performed.

2. General Tasking

The actual tasks were of two general types. The open-loop tasks consisted of requests to the subject to perform some mental exercise without the benefit of feedback of data. Typical open-loop exercises were the solution of simple mathematical problems. In all cases, the subject was specifically instructed to refrain from verbalizing in order to prevent mixing of the myogram (muscular) responses with the desired EEG. The most effective method of presenting open-loop tasks was to use prerecorded video tapes as the tasking medium. This method allowed the

research team to pace the subject in his tasks and maintained consistent tasking from subject to subject.

Closed-loop feedback tasks consisted of feedback by lights representing a code to the subject and controlled by the experimenter, and feedback of all the processed data via closed circuit television (CCTV). The CCTV allowed the subject to observe the same data seen by the research team. Investigations using closed-loop experiments were initially concerned with determining if the subject could control discrete frequencies of the displayed data.

B. ELECTRODES

The electrodes that were chosen for use in this project were made by Grass Instrument Company and consisted of a one centimeter diameter, cup-shaped silver electrode.

1. Properties of Electrodes

An electrode is the interface for the conversion of ionic currents in the conducting fluid of the tissue to electronic currents within wires and conversely. The conversion involves an electrochemical reaction at the metal/liquid junction.

Reversible electrodes are of three types [Ref. 1]; (1) a metal in contact with a solution containing its ions; (2) a metal in contact with one of its insoluble salts immersed in a solution containing the ion which combines with the metal to form the insoluble salt; (3) a noble metal in contact with a solution containing a substance in two valence states. Thus, reversible electrodes could be made from many different metals including copper, zinc, gold, platinum, silver, etc. The choice of an electrode requires consideration of such factors as degree of scalp irritation,

toxicity (zinc is highly toxic to humans, for example), skin staining and mechanical properties. A silver electrode meets the criteria quite well.

Since a silver electrode is a type 2 reversible electrode, it must be chlorided prior to use, the result being a silver:silver chloride (solid) electrode. The electrode to be plated is immersed in a saline solution (H_2O + NaCl) and connected to the positive terminal of a power supply. Another silver electrode is connected to the negative terminal and also immersed in the saline solution. A current is then established at a density of 1 ma/cm^2 of electrode surface area. The current is continued until the electrode is coated uniformly with a dark silver chloride surface (about 5 minutes).

The reaction that takes place at the anode is:

$$Cl^- + Ag \text{ (from electrode)} \rightleftarrows AgCl + e^-$$

2. <u>Conductive paste</u>

If current is to flow between tissue and a metallic circuit, the above reaction, which is reversible, takes place at the respective electrode-tissue interfaces.

Intimate contact between the electrode and scalp tissue is achieved by electrode paste consisting of sodium chloride in a gelatinous matrix. The electrode is held in contact with the subject by an elastic headband. The headband exerts sufficient pressure to hold the electrodes in place during mild movements by the subject.

C. EEG LEAD OFF

1. <u>Subject Ground</u>

Proper grounding of the subject is of extreme importance for several reasons. The primary reason is safety. In any experiment where

a human subject is directly connected to electronic equipment, caution must be exercised by the experimenter to insure that the subject is properly grounded. Significant potential difference between the subject and the equipment is always dangerous. This is particularly true when a low impedance connection is made to the body as with an electrode. A single ground system was used throughout the research project and each piece of equipment was tied to the same ground. The common ground was a water pipe ground, since the building grid system ground contained far too much noise.

The amplifier inputs presented a very high impedance to the signal lead electrodes. Thus, any current flow would be many orders of magnitude below a hazardous level.

The second reason for the importance of the ground electrode is its location at the neck level as explained in Section II. Not only does this placement shield the EEG from the EKG, it also serves to prevent contamination of the EEG with EMG signals and other electrical noise.

The screen room environment shields the amplifier from RF signals but is not effective in reducing the electromagnetic 60 Hz radiation present in every building. The body of the subject acts somewhat as an antenna and picks up a large amount of the 60 Hz signal. The ground at the subject's neck produces an effective ground plane. Thus, only that amount of 60 Hz received by the subject's head is present to contaminate the EEG. The resulting amount of 60 Hz contamination of the EEG is still quite unacceptable and is reduced much further by differential amplification techniques described later in this Section.

2. Unipolar

Unipolar leads were consistently used throughout the research project. In all cases, the reference electrode was the ear lobe of the

subject on the same side of the head as the active electrodes. The ear lobe is considered to be void of electrical signals emanating from the brain and, therefore, contains only electrical noise signals that are essentially common to the entire head. Thus the ear lobe is an ideal reference location for a differential amplifier input.

3. Location of Electrodes

Most of the experiments consisted of a set of four active electrodes plus the ear lobe reference electrode and the neck ground electrode. Eight active electrodes were available for usage and will be used in future experimentation.

The four active electrodes were consistently placed in the same general areas to maintain continuity from subject to subject and experiment to experiment. The locations chosen were the frontal, temporal, parietal and occipital regions. The side of head used was always opposite of the handedness of the subject in order to record from the dominant hemisphere. For example, a right handed person would have a dominant left hemisphere, and thus recordings would be taken from the left hemisphere. Figure 4-2 shows the locations of the four electrodes for the left hemisphere.

D. ANALOG SIGNAL CONDITIONING

One of the most critical aspects of the project was to amplify the EEG to a usable level without distortion or non-linear phase delay. Another factor of mutual importance was to eliminate the swamping effects of large 60 Hz signals present on the head and any other signals common to the reference electrode and active electrodes. The 60 Hz signal was expected to be much larger that the EEG.

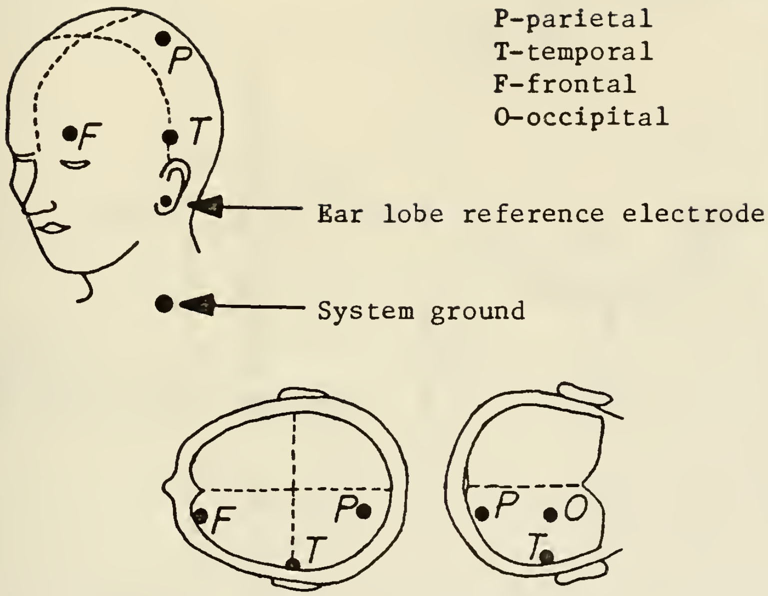


Figure 4-2. A perspective of electrodes in the standard positions used in the research project. Diagrams indicate the four left hemisphere positions used for a right-handed subject. Opposite hemisphere locations were used for left-handed subjects.

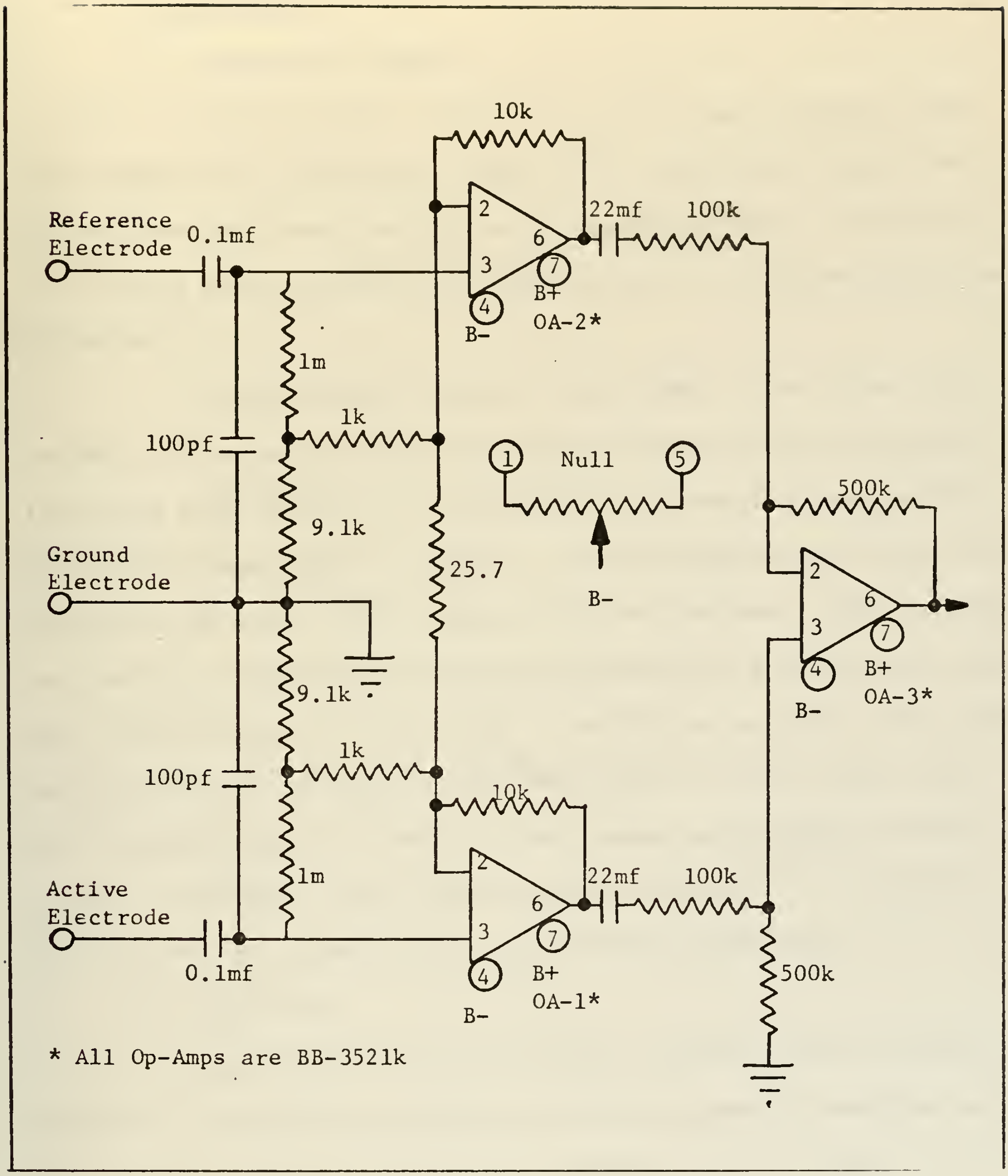


Figure 4-3. Two stage preamplifier schematic.

1. Preamplifiers

a. Differential Stages

The preamplifier consisted of a two stage amplifier with each stage having a differential input. The differential inputs were the ear lobe reference electrode and a signal electrode. The output of the input stage was then fed differentially to the second stage (see Figure 4-3).

The common mode rejection ratio (CMRR) of the first stage is 400:1 and the second stage was designed for about 60:1. The CMRR of the second stage depends on how accurately the components are matched. The overall design CMRR was 24000:1. The electrodes used as inputs had different lead lengths and slightly different impedances. This results in a portion of the common mode signal appearing as a differential signal, thus reducing the overall CMRR. The CMRR was measured under operating conditions (see Fig. 4-5) and was found to be over 6000:1 over the frequency range of interest. Thus, common mode signals were suppressed such that a common mode signal of 30 mV would be output with one tenth the amplitude of a 50 μV differential mode signal.

b. Low Noise

Amplification of a 50 μV signal requires a very low noise amplifier. A great deal of effort was directed towards obtaining the best quality, low noise, operational amplifier I.C.'s available. No commercial amplifiers were available that would meet the project specifications.

The operational amplifiers chosen were the Burr Brown 3521K with a low frequency or "popcorn" noise of 1.5 μV p-p for 0.01 Hz to 10 Hz and 2.5 μV p-p for 10 Hz to 10 KHz. Thus, amplifier noise was down at least 20:1 for a 50 μV signal.

c. Gain and Coupling

The gain equation of a non-inverting operational amplifier reduces to:

$$G = \frac{A}{1 + \frac{A}{(1 + \frac{Z_F}{Z_I})}} = \frac{1}{\frac{1}{A} + \frac{Z_I}{Z_F + Z_I}}$$

and for A >> 1

$$G = \frac{Z_F + Z_I}{Z_I}$$

The 3521K has an open loop gain (A) of 100 db or 10^5 and from figure 4-3:

$$Z_F = 10^4 \ \Omega$$

$$Z_I = \frac{25.7}{2} \ \Omega = 12.9 \ \Omega$$

The gain of the differential input stage becomes 770. The gain of the second stage is 5, thus the overall gain of the preamplifier is 3850.

Capacitive coupling was used as input coupling to prevent amplifier saturation due to D.C. electrode potentials. The research team felt it might be necessary to observe frequencies as low as 0.5 Hz so a 0.1 Hz cut off ensures that minimum phase distortion effects will be observed at 0.5 Hz.

2. Anti-Aliasing Filters

An anti-aliasing filter is used to suppress all frequencies greater than one-half the sampling rate. The filters are necessary because it is impossible for a discrete system of samples to distinguish between the samples contributed by a frequency of $f_{s/2} + \Delta f$ and $f_{s/2} - \Delta f$, where f_s is the sampling frequency. As an example, assume a sampling rate of 20 Hz and a sine wave of 10 Hz is to be sampled. Assume the

phase is such that samples are taken at multiples of $\pi/2$ or $\theta = n\pi + \pi/2$ and a sample is taken every 0.05 seconds. Now assume all the same conditions including the phase of the signal at the first sample are the same; however, replace the 10 Hz sine wave with a 15 Hz sine wave. Then the second sample will be taken at $\theta_2 = \pi/2 + 270°$, the third at $\theta_3 = \pi/2 + 2\pi + 180°$, the fourth at $\theta_4 = \pi/2 + 4\pi + 90°$, etc. But, this is exactly the same results as would be obtained if $\theta_1 = \pi/2$, $\theta_2 = \pi$, $\theta_3 = 3\pi/2$ and $\theta_4 = 2\pi$, etc. This last case corresponds to a frequency of one complete cycle every four sample times or $f_{s/4} = 5$ Hz. Thus the 15 Hz would masquerade as, or has an alias of, 5 Hz. The result is a folding of the higher frequencies into the frequency band defined by the sampling rate. Using the example above, 10 Hz to 20 Hz signals would alias as 10 Hz to 0 Hz signals, 20 Hz to 30 Hz signals would alias as 0 Hz to 10 Hz signals, etc.

a. Cutoff and Phase

The research team required the sensing of higher frequencies than were expected to be found in the EEG in order to assure that EMG signals were not mistaken for the EEG. EMG signals resulting from muscular activity in the head such as wrinkling the brow or clenching the teeth give rise to large amplitude signals covering the spectrum from D.C. to several hundred Hertz. Since essentially all EEG signals were expected to be less than 50 Hz, it was decided that observing signals to 100 Hz would satisfy the requirements. The filter was designed as a four pole Butterworth filter with a cutoff of 100 Hz. The response was down 3 db at 100 Hz and down 24 db at 200 Hz.

The choice of the Butterworth filter was due to its linear phase response. The filter phase response is very linear from 0 Hz to 50 Hz with a small amount of non-linearity fron 50 Hz to 100 Hz. The

phase response is quite acceptable for the less than 50 Hz EEG signals. The phase response shown in Figure 4-5 demonstrates the linearity. The low frequency phase is due to the preamplifier and capacitive coupling and not due to the filter.

b. Gain

The filter used Fairchild μA740 operational amplifiers. The filter has a gain of:

$$G = 1 + \frac{R_F}{R_I}$$

From Figure 4-4, the total gain from both stages is 2.57. The overall gain of the preamplifier system is then 9910 or about 10,000.

E. DIGITAL CONVERSION AND DATA STORAGE

The fundamental concepts and objectives of the research project specified in III constrain the processing media to be some form of a sophisticated, digitally controlled, signal analyser. The amount of required processing further constrained the analyser to meet "state of the art" time specifications. The best system available which met the specifications was the "1923 Time Series Signal Analyser" produced by Time Data Corporation of Palo Alto, California. The references to digital data and digital processing refer directly to the "1923 Time Series Signal Analyser".

1. Sampling Rates and Time

A sampling rate of 256 samples per second was chosen to conform with the Nyquist criteria for frequencies from D.C. to 128 Hz. The resultant frequency range is consistent with the myogram monitoring requirements specified above.

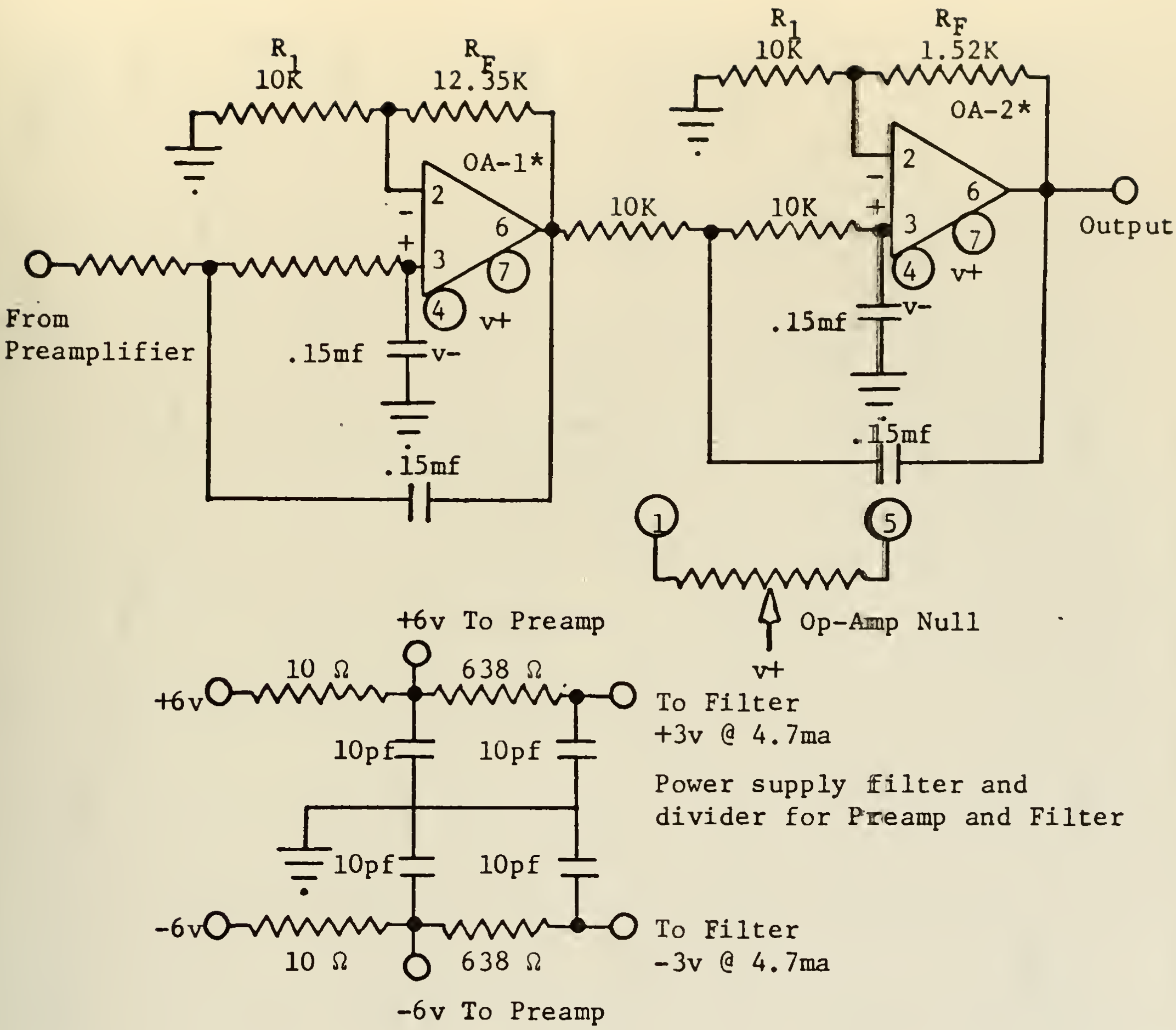


Figure 4-4. Four pole Butterworth Filter and power supply filter and divider for both Preamplifier and Anti-Aliasing Filter.

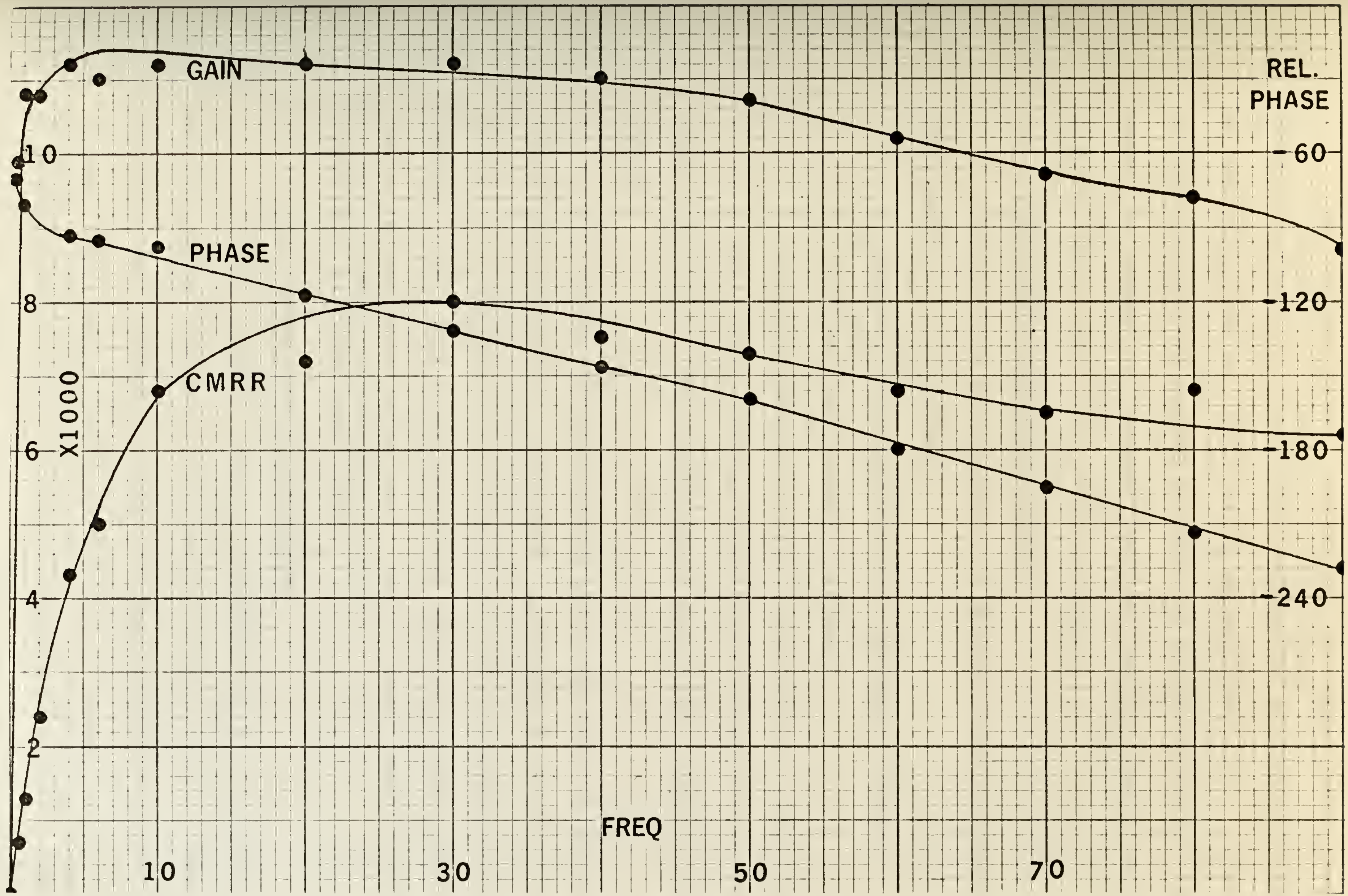


Figure 4-5. Gain, Phase and CMRR of preamplifier and filter system.

The original system configuration introduced four channels of EEG information into a four channel multiplexer with the 256 samples per channel per second. Each data frame consisted of one second of data per channel, for a total of 1024 data points per second. Each channel was sampled at the same time which precluded any possibility of an artificial phase delay between channels.

2. The Sliding Time Window Concept

The following factors and their desired range influenced the final choice of a time window:

a. Frequency determination up to one-fourth Hertz.

b. An update every second or oftener.

c. All processing to be completed within the update time.

d. Maintain statistical significance by processing a large enough data sample. The minimum sample length was considered to be two seconds.

The sliding time window meets all of the above criteria admirably. The sliding time window is achieved by collecting 4 s of data, processing that data, discarding the oldest second of data and adding the newest second of data. This results in 4 s of data for processing while maintaining the one second update rate. The 4 s window results in 4096 data points to be processed each second.

3. Data Storage Memory Requirements

The FFT algorithm converts time domain data to frequency data and the sliding time window requirements to reprocess the oldest three seconds of data results in a buffer storage requirement for 4K (K=1024) of data. Additional buffering is required as storage for the last 1K of incoming data while collecting the current 1K of data. Thus a total storage area of 10K is required to process four channels of EEG data.

Each of the buffers 4s' of data must be edited each second to maintain the correct descending time order. In reality the 4K buffer is four 1K buffers, one for each channel.

4. Real Time Requirements

The ability to process data in real time was one of the specific objectives of the research effort from the inception of the idea. Real time analysis offers numerous advantages over off line processing. Some of the advantages are (1) avoidance of the long time delays between the performance of an experiment and the availability of the processed results, (2) the flexibility to use dynamic experimental techniques, that is to modify an experiment based on the results of the experiment, and (3) assurance that all systems are performing correctly and that time is not wasted on collecting erroneous data. The prime disadvantage to real time data analysis is the severe time restrictions and large memory requirements. This makes it absolutely necessary to use "state of the art" equipment to obtain the required speed and further requires the experimenters to be thoroughly familiar with machine language programming so that they can take advantage of every time saving programming feature available.

F. DATA PROCESSING HARDWARE AND ALGORITHMS

The data was processed in a number of ways in order to look at its different aspects. For example, in spectral displays the magnitude of the Fourier transform gave information about the frequency components present in the time window for the individual channels. The magnitude of the cross-spectrum gave information of frequencies common to two channels. The spectral formatted EEG was termed a spectral encephalogram (SEG).

The time domain analysis was done by first taking the discrete Fourier transform, then performing digital filtering and then taking the discrete inverse transform. These were then designated time encephalograms (TEG).

The SEG analysis showed at what frequencies interesting signals occurred. Since the SEG was an average spectrum over the time window, information concerning the amplitude and length of the signals was not available. The TEG analysis allowed the experimenters to observe the shape, amplitude and time course of the frequency bands of interest.

Time domain analysis also included the auto- and cross-correlations. The autocorrelation was of interest because it gave the relative power and average duration of signals in a specified frequency band. The cross-correlation gave the same results between two channels.

Each of the algorithms and analysis programs used in the project is discussed below.

1. FFT

The signal analyser used by the research team includes a separate hardware FFT processor called the F-4. The F-4 operates as a separate processor to the main frame CPU and performs the discrete Fourier transform (DFT) on a 1K block of data in 90 ms. In a standard four channel 4 s time window, 36% of the available processing time is consumed by the FFT.

a. FFT Algorithm Implemented in Hardware

The DFT performed by hardware is expressed by:

$$F_i = \frac{1}{N} \sum_{k=0}^{N-1} X_k \exp(-j2\pi ik/N) \quad \text{where } i = 0,1,\ldots,N-1 \text{ [Ref.12]}$$

where F_i is the ith coefficient of the DFT and X_k is the kth sample of

the time series which consists of N samples. The F_i's are almost always complex and the X_k's may be complex.

The fast Fourier transform (FFT) is so called because of the increased speed of calculation as opposed to the direct method. The FFT is merely the actual algorithm which is implemented to obtain the DFT. The particular FFT used by the F-4 is called "Decimation in Time;" and was first proposed by Cooley and Tukey in 1965 [Ref. 12]. The speed improvement is achieved by a reduction in the number of multiplications required in the FFT due to a decimation of the input function into separate sine and cosine harmonic components of the lowest recognizable frequency. The approximate upper bound on the ratio of the number of multiplications required by the DFT compared to the FFT is:

$$\frac{N}{2 \log_2 N}$$

For a 1K point transform, this would amount to a 50:1 time savings if a machine were used in which the time required to obtain the DFT were approximately proportional to the number of multiplications required. In other words, without the FFT algorithm, the 90 ms 1K DFT would require as much as 4.5 s. Obviously the real time requirements could not be met without the FFT algorithm.

b. IFT

The algorithm for calculating the discrete inverse Fourier transform (IFT) is very similar to that for the DFT. The form of the inverse is:

$$X_m = \sum_{i=0}^{N-1} F_i \exp(j2\pi im/N) \quad \text{where } m = 0,1,2,\ldots,N-1$$

The validity if the inverse may be shown by substitutions:

$$X_m = \frac{1}{N} \sum_{k=0}^{N-1} \sum_{i=0}^{N-1} X_k \exp(-j2\pi ik/N)(j2\pi im/N)$$

or:

$$X_m = \frac{1}{N} \sum_{k=0}^{N-1} X_k \left(\sum_{i=0}^{N-1} \exp(j2\pi i/N)(k-m) \right)$$

It follows that the left and right hand sides are equal from the orthogonality relationship:

$$\sum_{i=0}^{N-1} \exp(j2\pi i/N)(k-m) \quad = N, \text{ for } k=m$$

$$= 0, \text{ otherwise}$$

This follows from the fact that:

$k = 0,1,2,\ldots,N$

$m = 0,1,2,\ldots,N-1$

therefore:

$1-N \leq (k-m) \leq N$

2. <u>Auto-Spectrum and Magnitude of the FFT (SEGs)</u>

The auto-spectrum is the standard function defined as:

$$S_{AA}(x) = |F_A(x)|^2 = F_A(x)\ F_A(x)^*$$

$$= \left(R_A(x) + j\ I_A(x)\right)\left(R_A(x) - j\ I_A(x)\right)$$

$$= R_A(x)^2 + I_A(x)^2$$

The auto-spectrum is a measure of the power of the frequency components. Since the FFT is taken for a particular time window, then the amplitude of any specific frequency component is dependent on both the amplitude and duration of the frequency during the time that the sample was taken. Therefore, the auto-spectrum is a measure of the amplitude and durations of the frequencies present. Consider the case of the 4 s time window and some specific frequency event occurring

during the latest second of data. The contributions to $S_A(x)$ due to the event will be present, at a constant magnitude, during the first time that data second is processed and for the next three successive seconds. This serves to demonstrate the lack of time and phase information in the auto-spectrum and points up the need for different analysis routines to obtain this information. Although it may be argued that time and phase information is available in the complex discrete Fourier series, the format is not of the type easily assimilated by man, particularly in a real time situation with a one second data rate.

The magnitude of the FFT is easily obtained by taking the square root of $S_A(x)$. The time restrictions mentioned before made it necessary to perform the square root as efficiently as possible. A fast square root algorithm was written that performed the square root of a 1K block in an average time of 23 ms. The algorithm was accurate beyond the significance of the data.

3. <u>Cross-Spectrum</u>

The cross-spectrum of any two signals is a measure of the commonality of the frequencies of one signal to those of another signal. The cross-spectrum of channels A and B used in this research project is actually the magnitude of cross-spectrum and is defined as:

$$S_{AB}(x) = |F_A(x)|\,|F_B(x)|$$

4. <u>Reconstituted Time Domain Signals (TEG)</u>

The TEG signal is achieved by an ideal digital filter (IDF); that is, all unwanted frequencies are zeroed in the DFT and then the IFT is performed on the remaining frequency domain signal. The important point is that both real and imaginary terms of the desired band pass are unaffected and therefore the TEG signal maintains the same phase and amplitude relations, over the pass band, as the original input signal.

5. Autocorrelation Function

The time autocorrelation function is defined as:

$$R(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} f(t)\ f(t + \tau) dt$$

and has three particularly useful properties:

a. The autocorrelation has a maximum value at the origin.

b. R(0) is the mean squared value of f(t).

c. $R(\tau)$ is an even function so that only $R(\tau)$ for $0 \le \tau \le T$ need be calculated.

The autocorrelation function is achieved by taking the IFT of F(f) multiplied by its conjugate. Since multiplication in the frequency domain corresponds to convolution in the time domain, then conjugate multiplication in the frequency domain corresponds to a time reversal convolution, or correlation, in the time domain.

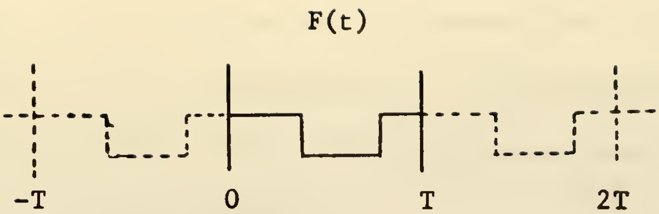
The use of a Fourier series implies a periodic function such that the IFT of the conjugate multiplication would result in a time domain signal that folded or wrapped around itself. This problem was eliminated by tne "zero insertion". Zero insertion is the process of doubling the range of the time domain data and filling the added half of the block with zeros (see Fig. 4-6).

When signals are distributed in the non-zero half of the block, on the average the autocorrelation will appear as if a weighting function had been applied. This weighting function will taper linearly from a maximum at τ=0 to zero at τ_{max}.

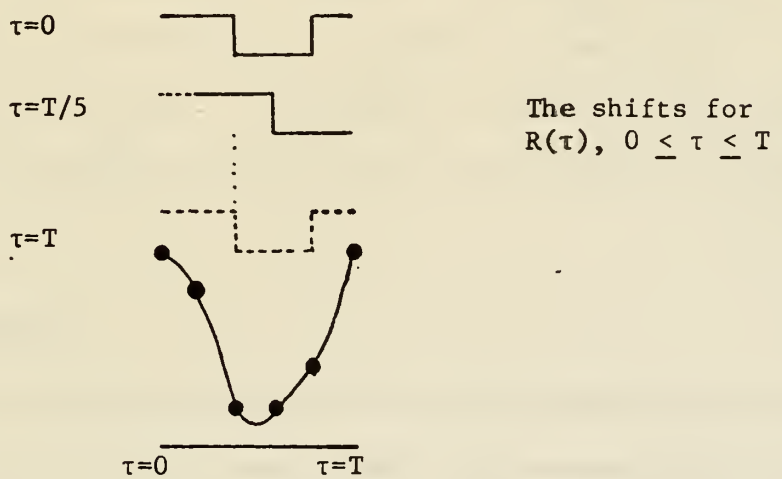
6. Cross-Correlation Function

The cross-correlation function is defined very similarly to $R(\tau)$ as:

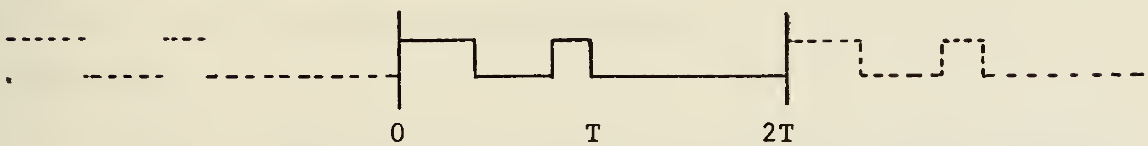
$$R_{xy}(\tau) = \lim_{T \to \infty} \frac{1}{2T} \int_{-T}^{T} x(t) y(t + \tau) dt$$



The original time window and signal (without zero insertion) with the repetition implied by the use of the DFT.



The result of autocorrelation.



The time window after zero insertion with the repetition implied by the use of the DFT.

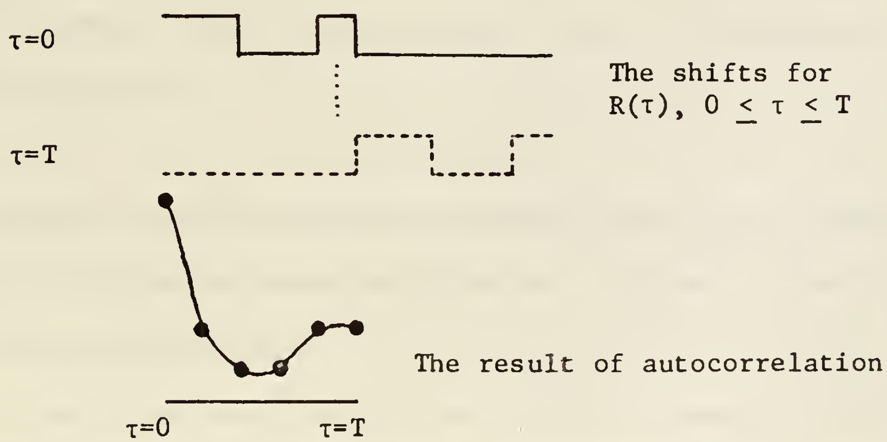


Figure 4-6. The use of zero insertion with autocorrelation.

and is computed much the same as $R(\tau)$ except that $F_x(f)$ is multiplied by the conjugate of $F_y(f)$, zero insertion is applied, and the IFT performed.

The properties of the cross-correlation are somewhat different from those of the autocorrelation:

a. The maximum value does not necessarily occur at the origin.

b. Since the imaginery components of $F_x(f)F_y(f)^*$ are not in general zero, then the function is not, in general, symmetrical.

c. $R_{xy}(\tau) = R_{yx}(-\tau)$. It should be noted that $R_{xy}(\tau)$ may have the same type of weighting function as the autocorrelation with zero insertion.

G. ANALYSIS PROGRAMS

The analysis programs discussed in this section were conceived, designed and developed by the research team. The programs evolved from very simple early ones to the sophisticated, multi-dimensional analysis routines such as MIXFM. The evolutionary process was a result of learning what to look for and how to look for it.

1. <u>FSEG</u>

FSEG is a display of the magnitude of the DFT of four channels of EEG. The data is processed using a four second sliding time window and the data is updated at a one frame per second rate. The frequency range was from 0 to 128 Hz.

2. <u>XSEG</u>

XSEG represents the six different cross-spectrums of four channels of EEG. The number of different cross-spectrums for n channels of data is given by the binomial coefficient.

Each cross-spectrum trace displays the frequency range 0 - 128 Hz and consists of four seconds of data using the four second sliding time window. The update rate was one frame per second.

3. TEG4A

It was decided that it was necessary to look at the time domain EEG with bandpass limited data. The necessity arose from a desire to observe time and phase relationships of various signals without the swamping and distorting effects of the full band data. The ability to perform ideal digital filtering resulted in the TEG4A analysis routine.

TEG4A consists of four data channels of EEG with each channel separately bandpass-limited over the range of 0 to 128 Hz. Each data trace of each frame represents two seconds of data resulting from a two second sliding time window. The oldest data second occupies the left edge to the middle of the trace and the latest second runs from the middle of the trace to the right hand edge. On succeeding frames, the left half of the trace is replaced with the previous right half of the trace.

TEG4A is used to display the same channel of EEG on each trace with each trace having one of four different pass bands. Thus, a signal may be dissected into four different bands for determination of frequency-phase relationships within a single channel of EEG. An alternate usage of TEG4A is to display four different channels of EEG each with the same pass band. Thus four channels of EEG may be bandpass limited for determination of channel-phase relationships within a single frequency band of EEG. Any other combination of from one to four channels of EEG may be dissected into from four to one bands, respectively.

4. MIX1

MIX1 is a multidimensional analysis program capable of showing the full frequency EEG signal, the spectrum of the signal and two band limited dissections of the time domain signal with their respective

autocorrelations for a single channel of EEG. MIX1 was based on a two second sliding time window with a one second update rate.

The six traces displayed by MIX1 have the following information:

a. The first trace consists of two seconds of TEG information achieved by taking the IFT of the entire spectrum. No digital filtering is performed.

b. The second trace is FSEG. It shows the magnitude of the frequency components from 0 to 128 Hz in 1/2 Hz resolution.

c. The third trace is a two second TEG, bandpass limited. The passband is independently selectable by the operator.

d. The fourth trace is the autocorrelation of trace three. The lag variable, τ, ranged from 0 to 2 s from left to right.

e. The fifth trace is another TEG trace for a different band than trace three.

f. The sixth trace is the autocorrelation of trace five.

5. XCORR

XCORR is based on a 2 s sliding time window with a one second update time. It computes and displays three trace pairs of the cross-correlations of three channels of EEG each cross-correlated against a fourth channel. The frequency band over which the cross-correlation is performed is operator selectable. Of each trace pair, the first trace displays, left to right, tau from zero to +2 s and the second trace displays, left to right, tau from -2 s to zero.

XCORR can be used in one of two modes, the first mode having been indicated above where the reference channel was a channel of EEG. A second mode was available when the reference channel was replaced with the signal of an external generator. The external signal used was a

swept FM signal with the same frequency limits as defined for XCORR. The FM sweep rate was generally between one and two sweeps per second to maintain compatability with the program update rate.

It should be noted that the external signal results in a chirp signal and acts as a chirp sifter in that any tendency of the EEG signal to chirp at a rate reasonably close to the rate of the external signal will result in a spindle shaped portion of cross-correlation with significantly larger amplitude than other cross-correlations. The actual amplitude and length of the spindle will depend on the sweep range of the EEG signal, the amplitude of the EEG signal and the relative equality of the sweep rates of the two signals.

6. MIXFM

MIXFM represents a very sophisticated multidimensional analysis routine. It includes the full band time domain signal, full band frequency spectrum, band limited TEG and band limited frequency spectrum, with a separate gain, of a single channel of EEG. It also contains a machine created swept FM signal and the FM signals' spectrum. The swept FM has the same frequency limits as the TEG signal and has a sweep rate of once every 2 s. MIXFM also displays the corss-correlation of the band limited EEG signal with the swept FM signal.

The cross spectrum trace has an advantage over that of external mode XCORR in that the swept FM is digitally controlled to sweep from its low frequency to its high frequency in exactly 2 s and always starts from the low frequency point at time equals zero referenced to each data frame. Since the frame time and FM signal time relationships are fixed and since the cross-correlation function represents a sliding of one signal with respect to another, additional data is readily available

in MIXFM as compared to XCORR. For example, the first incremental slide in the positive tau direction means the highest frequency of the FM signal is lost and lower frequencies are lost as the sliding is continued. Defining τ_z as the point at which the cross-correlation goes to zero and remains at zero until the end of the trace, then the lowest frequency present in the EEG signal would be:

$$f_{low} = f_{min} + \left(\frac{\tau_{max} - \tau_z}{\tau_{max}}\right) (f_{max} - f_{min})$$

where f_{max} and f_{min}, respectively, are the highest and lowest frequencies of the swept FM signal and where τ_{max} equals the maximum value of tau. Since the same information is available in the band limited FSEG, the real significance is the ability to determine f_{low} for any arbitrary amplitude. Assume one wished to determine the lower bound on the frequencies that contributed a cross-correlation amplitude of at least half or more of the maximum cross-correlation amplitude. τ_z would then be selected such that no cross-correlation was greater than half of the maximum cross-correlation amplitude from τ_z to τ_{max}. This information is not available from FSEG since FSEG is the average DFT over a two second interval and the amplitude of the frequency components is a function of the amplitude of the frequency and the length of time the frequency is present. The same calculations applied to the negative tau direction will give the upper bound, at a given amplitude, on the frequency of the EEG signal.

The value of MIXFM is that it enables one to determine the frequency components of a TEG waveform more accurately than could be done with TEG4A.

The initial display of MIXFM consists of the time domain representation of the machine created swept FM signal on trace one and the

magnitude of the spectrum of the FM signal on trace two. The remaining traces are blank. Succeeding frames of MIXFM display the following information.

a. Trace one is the full band TEG of the EEG channel.

b. Trace two is the full band FSEG.

c. Trace three is the magnitude of the digitally filtered spectrum of the EEG and has an independent gain factor such that the frequencies of higher bands can be seen more readily.

d. The fourth trace consists of the band limited TEG signal.

e. The fifth and sixth traces are the respective positive and negative ranges for the cross-correlation.

H. ANALYSIS TOOLS

The above discussions have defined the various analytical tools that were brought to bear on the problem of analysing the human EEG. A consolidated listing of these tools is as follows:

(1) <u>Real Time</u>

(2) <u>Multiple Channels</u>

(3) <u>Magnitude of Fourier Series</u>

(4) <u>Auto-Spectrum</u>

(5) <u>Cross-Spectrum</u>

(6) <u>Ideal Digital Filtering</u>

(7) <u>Band Limited Time Domain</u>

(8) <u>Autocorrelation</u>

(9) <u>Cross-Correlation</u>

(10) <u>Cross-Correlation With An External Signal</u>

The list is an impressive array of computational effort and represents a very serious attempt at real time analysis of the on-going EEG.

I. ON LINE DATA DISPLAYS

The operator is presented with two on line data displays. The first is an analog display. The analog signal from the anti-aliasing filter is fed to an HP-141B variable persistence storage scope. The scope is set to a one second trace rate and displays four channels of EEG continuously. The operator can monitor the four channels of EEG to ensure that all electrodes are functioning properly, that there is no EMG on the signal and that each channel's amplifier and filter is functioning correctly.

The second display is a memory scope that displays the results of the various analysis programs. The display scope is an integral part of the Time Data Signal Analyser.

The operator also has two lights, one of which indicated the beginning of a problem presented to a subject via video tape and the other which was activated by a subject indicating the completion of an assigned problem.

J. DATA RECORDING

The method of obtaining hard-copy data was via a 16mm movie camera (Paillard, Bolex). The camera was used in the single frame mode and was actuated by a solenoid.

The camera photographed a standard, large screen, HP-1300A oscilloscope. The photograph included a digital frame counter and two lights, one indicating the start of a new problem and the other indicating the completion of an assigned problem. These lights were in parallel with the lights at the operator's panel. The frame counter was advanced by a pulse from the processor during each processing cycle and this same pulse was used to synchronize and advance the camera. Thus, the camera

took a photograph of a data frame every second. Reels of film 100 feet long were used and each reel held about 4000 frames of data representing over an hour of processed EEG data.

The film was viewed for analysis using a Kodak analysis projector (Kodak Analyst) which had two operating modes. One mode allowed the operator to single step frames by pushing a button. The automatic mode had automatic rates of one, two, four, eight, twelve, sixteen and thirty-two frames per second. Each mode allowed both forward and reverse operation.

During each data run, an operator made notes on a dictaphone which were later transcribed and filed with the associated reel of film.

V. RESULTS AND ANALYSIS

A. OBJECTIVES

The objectives were to determine the constituent parts of the EEG by dissecting the EEG into preferred frequency bands and time series signals. Further objectives were to distinguish those frequency bands and time series signals associated with mental effort from those associated with states of relaxation.

B. DISSECTION OF THE EEG

1. Composition of the EEG

The EEG consists of spindle shaped envelopes of sinusoidal waveforms which are algebraically added to produce the resultant EEG. This is an observed fact shown by experimental results.

a. SEG Experimental Results

The frequency band from 8 to 12 Hz has been termed the alpha band and a predominant frequency within that band of about 10 Hz is generally referred to as the alpha frequency. This particular alpha frequency has received a lot of attention over the years primarily because it is a large amplitude signal easily observable and remarkably consistent from subject to subject. Certain characteristics of the alpha frequency have been known for some time and were phenomena responsible for millions of dollars and many man-years of research effort. The characteristics of alpha well documented in past research and confirmed in the very early stage of this research effort are the ease with which a subject may be taught to generate large amounts of alpha by closing his eyes and the use of the simplest forms of feedback to indicate when the subject

is producing alpha. A second characteristic is the dramatic decrease in the amount of alpha present when a subject opens his eyes, and a third characteristic is a further reduction in alpha when a subject is tense or involved in mental effort concerned with some form of problem solving.

Consideration of the obvious preferred frequency of alpha and certain other preferred lower frequencies led us to suspect that there might be other preferred frequencies with definite characteristics associated with the frequency and time domains. The SEG and the XSEG programs were used to observe the frequency spectrum of the EEG and to determine how the time average spectrum varied with time. Frequencies were found that had much larger amplitudes than nearby frequencies and it was noted that the amplitudes of these interesting frequencies varied significantly as a function of time. Figure 5-1 is an example of a frame of SEG indicating the presence of relatively large amplitude, discrete frequency components of the EEG.

Further investigation of preferred frequencies included feeding the entire spectrum of the EEG back to the subject and asking him to attempt to enhance a particular frequency component. Figure 5-2 is a frame of SEG data showing the results of asking a subject to enhance the presence of 20 Hz. Feedback to the subject did not result in a constant large amplitude 20 Hz component, rather the 20 Hz component fluctuated with time but the peak and average amplitude of the 20 Hz were significantly increased over that obtained without feedback to the subject. It should be noted that the feedback of alpha also results in a fluctuating alpha component whose peak and average values are significantly increased over those obtained without feedback.

Other preferred frequencies are indicated in the 14-30 Hz range of Figures 5-1 and 5-2. The presence of discrete frequencies

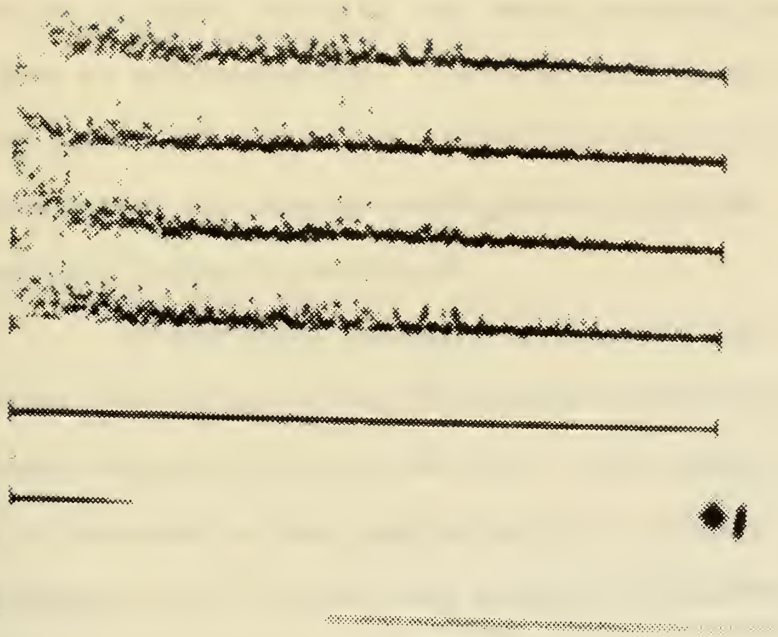


Figure 5-1. A frame of FSEG showing large amplitude, discrete high frequencies. The traces, from top to bottom, are F,T,P,O. The frequency range is 0 to 128 Hz with 12.8 Hz per division. Discrete frequencies are seen at 19 Hz, 33 Hz, 42 Hz, 48 Hz, 58 Hz and 63 Hz.

higher than 30 Hz is indicated. A most remarkable characteristic of the preferred frequencies is their discrete nature. This means that these signals are quite pure, single frequency sinusoids. The presence of pure sinusoids as the resultant waveform contributed by large groups of neurons strongly indicates that neuron groupings must be working in some form of synchronization. Synchronization alone does not account for the remarkably pure sinusoids that are shown to exist; however, synchronization via feedback could produce sinusoids. This theme will be developed further in section VI.

An additional parameter of the spectrum of the EEG was established with the use of the SEG and XSEG programs which showed that when one preferred frequency went down, others might come up. This might be explained as some type of partial frequency exclusion. That is, the presence of one frequency may preclude the presence of some other frequency or frequencies. An alternate and preferred explanation stems from consideration of synchronous activity of neuronal groupings. The establishment of synchronized activity in a group of neurons by means of feedback would be self perpetuating until such time as neuronal fatigue should preclude any further activity of that area. If the synchronized activity of one area is used as a stimulus to initiate activity in other areas, then the other areas would be expected to synchronize to large amplitude sinusoids also. Some time delay would be expected after the initiating area became synchronized. Assume the time delay required before synchronization can take place is on the same order of magnitude as the length of time an area can remain in synchronization prior to neuronal fatigue. If the different areas have different synchronization frequencies, then the apparent result would be the loss of some frequency components accompanied by the enhancement of other components. This type

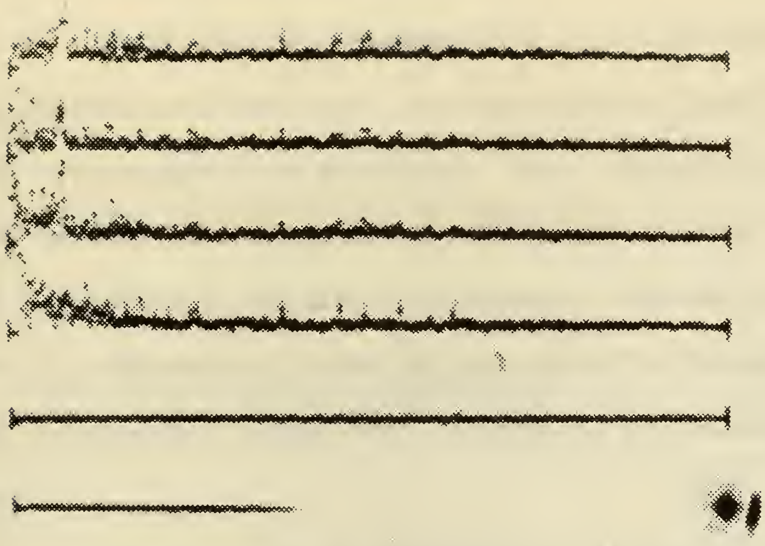


Figure 5-2. A frame of FSEG with the same parameters as 5-1. The subject saw the data as feedback and was asked to enhance 20 Hz on the third trace. The actual frequency is 19.5 Hz and it is much larger than any signal near it on the third trace.

of behavior is seen in SEG displays. The initiation of synchronous activity in a large area due to activity in another area is an example of what is termed recruiting.

b. TEG Experimental Results

Since the SEG programs gave an average over the epoch and it was desired to investigate the time course of specific frequency bands, the TEG type program was developed. Ideal digital filtering allowed sharply defined pass bands whereby the signal in the pass band did not suffer from phase or amplitude distortion. The use of TEG programs resulted in a dissection of the EEG into specific frequency bands of time domain information. These were referred to as reconstituted time domain signals.

The spindles of sinusoidal oscillations were more clearly revealed and were observed to have the characteristic that oscillations in one band were not necessarily coincident with those of another band.

Specific effort was directed toward proving or disproving the idea that the observable higher frequencies in the spectrum of the EEG might be merely harmonics of the lower frequencies. This idea accounts for the harmonics as the result of non-linear processes in the cortex. Apparent harmonic frequencies of the alpha frequency were detected in the 20 Hz and 30 Hz bands. The TEG4A program was developed and a single channel of EEG was displayed with traces showing the full band TEG, the alpha band TEG, the 20 Hz band TEG and the 30 Hz band TEG. Figure 5-3 is an example frame of the described experiment.

The waveforms of the various traces of Figure 5-3 show that the harmonic frequency band spindles are not coincident with those of the alpha spindles and it further shows that there is not any type of

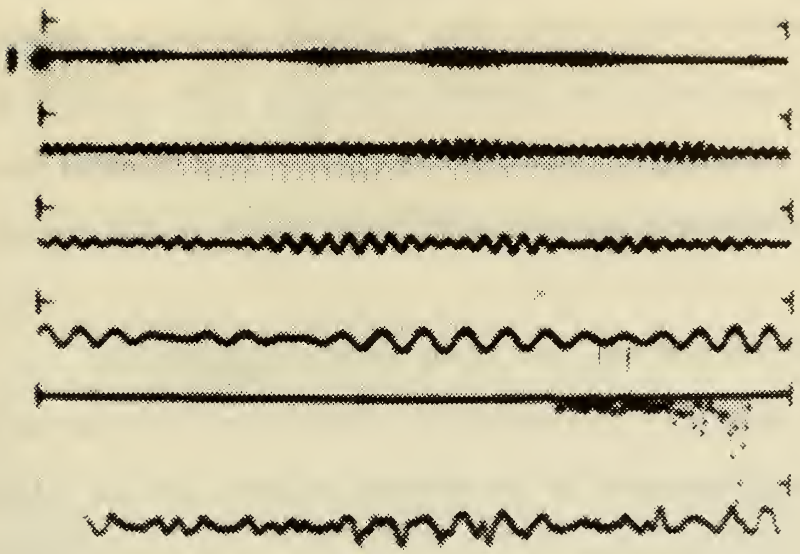
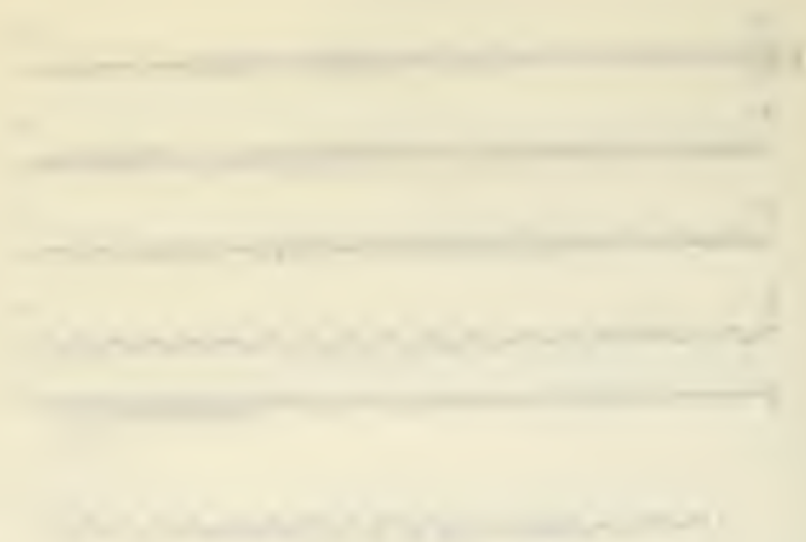


Figure 5-3. Results of the experiment showing that frequencies at 20, 30, and 40 Hz were not harmonics of 10 Hz. The first trace is two seconds of an 8-42 Hz TEG signal. The second trace is FSEG for the band of interest (8-42 Hz). Trace 3 is 2 seconds of TEG for 8-12 Hz, trace 4 is 18-22 Hz, trace 5 is 28-32 Hz and trace 6 is 38-42 Hz. Each band shows at least one spindle at a time that corresponds to a zero value on at least one other trace. Thus, the signals are harmonically related to 10 Hz, but are not harmonics of 10 Hz. It should be noted that end effects have been checked for the reconstituted time domain signals. The end effects do not go beyond 0.1 s on either end of the signal.



time delay of onset of a spindle that is proportional to the frequency band. Consecutive frames for this experiment show that the phase relationship of the spindles of the various bands is not fixed and appears to shift at random. That is, the 10 Hz spindle may lead ahe 20 Hz and the 20 Hz spindle may lead the 30 Hz in one frame and the lead-lag relationships may change randomly with other frames and sometimes within a single frame. This experiment totally disputes the above mentioned idea and is sufficient evidence to consider the higher frequency components of the EEG as actual electrical signals separately generated by the brain.

It was stated previously that the EEG was composed of the algebraic addition of spindles of sinusoidal waveforms of various frequencies. In Fig. 5-3 the application of superposition yields the composite EEG.

c. Further Spindle Analysis.

It was noted that within certain bands the spindle patterns seemed to have considerable variability. A specific example is shown in Figure 5-4 which is a classic example of a waveform originally referred to as an 'M-wave' because of its shape. The relative rarity of the M-wave and its very distinctive shape led to the conclusion that the M-wave was a specific signature of the brain indicating some form of response to an event. However, the application of MIXFM yielded an entirely different explanation.

(1) MIXFM Analysis. The presence of FM signals within the EEG was suspected and the need to confirm the presence of FM components as well as the need to exactly identify the frequency components of the more curious spindles led to the development of the MIXFM program. It will be recalled that MIXFM contained an FM sweep extending from the low

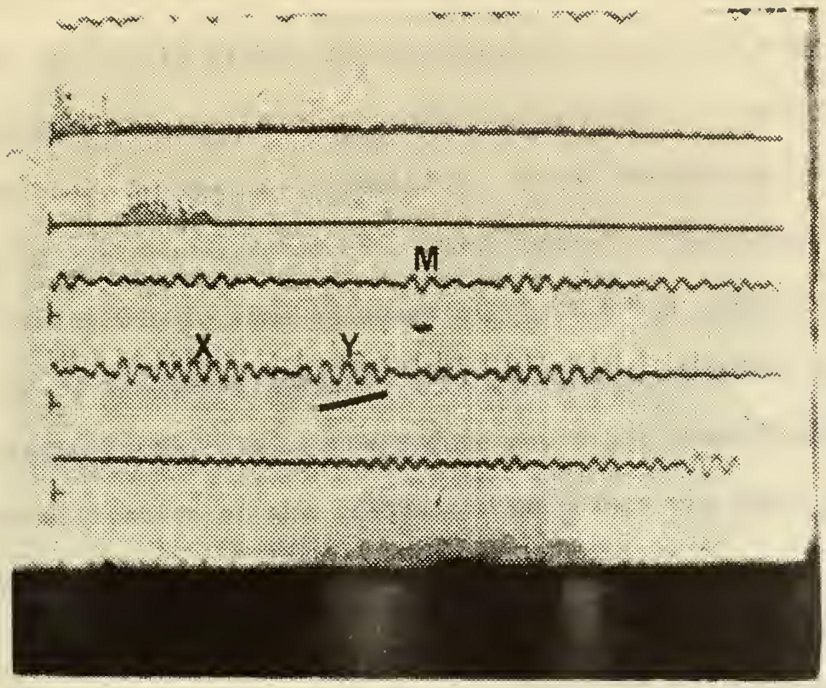


Figure 5-4. A sample frame of MIXFM. Only five traces are shown. Trace 1 is the full band FSEG, trace 2 is the band of interest FSEG. Note the higher gain used on trace 2 and the discrete frequencies at 14, 15.5, 16.8 and 18.8 Hz. Trace 3 is the band limited TEG, with the M wave marked. The cross-correlation of trace 3 with the machine created sweep is shown in traces 4 and 5. Trace 4 shows, left to right, 0 to 2 s. Trace 5 is right to left, 0 to -2 s. The spindles X(18.8 Hz) and Y (15.5 Hz) are the only components of the M-wave shown in this frame.

to the high frequency limits of the band, and that this was cross-correlated with the TEG response. The presence of an FM signal within the TEG band would result in a spreading of the cross-correlation because the rate at which the frequency changed would most probably be different for the TEG FM signal and the machine created FM signal. If the machine FM sweep and the FM of the EEG should happen to agree, the result would obviously be the large amplitude, short duration waveform characteristic of the autocorrelation of a chirp signal. The presence of a small amount of FMing within some spindles of the EEG was confirmed. The identification of frequency components of particular spindles was achieved specifically in th case of the M-wave and other unusual spindle patterns. The identification of the frequency components was done in the following manner.

First a computer generated plot on paper was produced with the same FM sweep limits as called for in the MIXFM program. The time scale was set to some fairly large value. For example, the sweep may extend from 14 to 30 Hz with one inch representing 0.2 seconds, thus the plot would encompass 10 inches. The projector was then set such that the 2 second traces of τ for the cross-correlation and time for the TEG signals exactly matched 10 inches of the separate FM sweep plot. The data was superimposed by projections on the FM sweep plot and a frequency match was found with the spindle in the cross-correlation trace. The amount of offset, left or right, of the FM sweep plot required to obtain a frequency match in the cross-correlation trace corresponded to the amount of τ, negative or positive, which in turn corresponded to the minus or plus time shift required before correlation was achieved. The same amount of shift of the FM sweep plot was then incorporated with the TEG signal superimposed and the frequency point found in the FM sweep

plot previously now lined up exactly with the portion of the TEG signal in which that frequency was found. In this manner all of the frequency components and their durations of a segment of TEG were determined accurately and quickly. The presence of FM signals within the TEG were indicated by continuously changing frequencies in the cross-correlation with a continuous area of origination within the TEG trace. Figure 5-4 cites an example of the analysis technique applied to an M-wave and shows the components of the M-wave. Since adjacent data frames incorporated both the newest second and previous second of TEG data, a complete analysis of any amount of TEG could be easily accomplished by analysing the required number of data frames.

(2) Pass Band Reduction Analysis. Further analysis of the M-wave via MIXFM indicated that the waveform was made up not only of 16 Hz and 19 Hz components, but included a small amount of 22 - 25 Hz FM. These frequencies were also found in other spindles that did not have the characteristic M shape.

Continued investigation of the M-wave was done with the use of the TEG4A and narrow bandpass limits to incorporate the 17 Hz, 23 Hz and 28 Hz bands. It was confirmed that responses such as the M-wave were indeed composed of spindles of the above frequencies (Fig.5-5). However, the same spindles were present quite often without the characteristic M-wave. The M-wave then is not a characteristic response but merely the random algebraic addition of the three spindles.

d. Tegule

The previous results led to the concept of "tegule". The tegule was proposed as a unit signature of cortical activity. The appearance of a tegule would be that of a fairly uniform spindle envelope

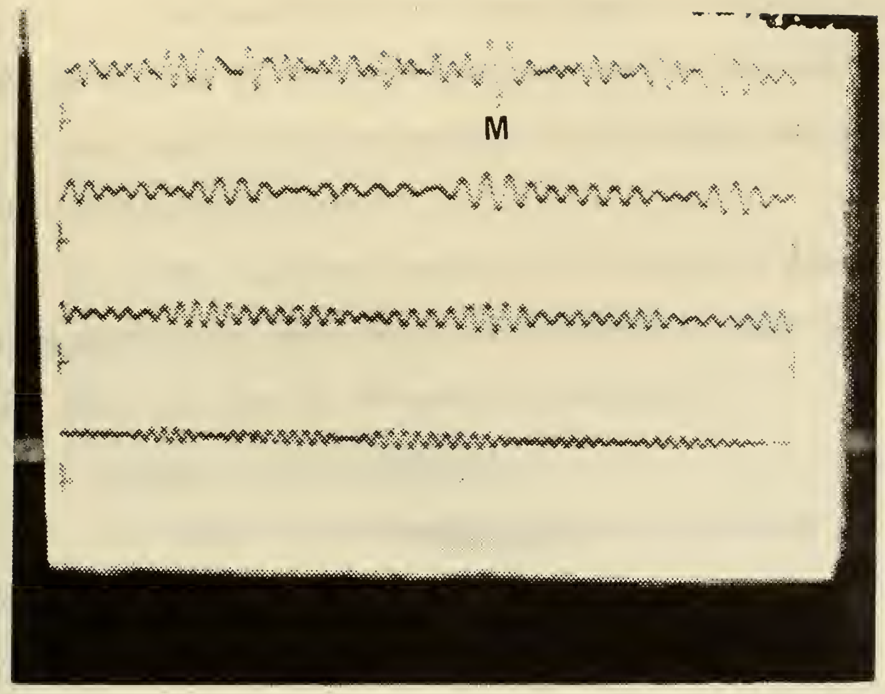


Figure 5-5. A sample frame of TEG4A with pass bands of 14-36 Hz, 22-26 Hz, 26-30 Hz and 30-36 Hz from the top to the bottom traces. Note the variability of the spindle patterns between traces and within traces. The classic M-wave shown in trace 1 is composed of 22-26 Hz and 26-30 Hz spindles and a small amount of 30-36 Hz.

enclosing a sinusoid. The sinusoid frequency would be expected to vary slightly with lower frequencies at the end points and the highest frequency at the center, maximum amplitude point of the spindle.

The proposition that the tegule of a particular frequency might have a set of discrete durations will be discussed in section VI. It is also argued that the duration of the tegule would vary inversely with the spindle frequency.

The tegule may arise as the stochastic summation of the concerted activity of nerve cells in a relatively small region of the cortex. This will also be discussed in section VI.

2. <u>Proposed Tegule Confirmed</u>

The tegule is the result of cortical activity in a definable region of the cortex. The size of the region generating a tegule is shown to be inversely related to the frequency of the tegule's sinusoidal component.

a. Tegule Independence Experiment

An experiment was designed to test the hypothesis that higher frequency tegules were associated with smaller cortical regions. Four electrodes were spaced about 2 cm apart on a subject's scalp. Measurements were taken in order to map the locations of the electrodes accurately for repositioning in later experiments. The electrodes were arranged in a diamond pattern within the parietal area. TEG4A was used to display the same frequency band for each of the electrodes. The programs FSEG and XSEG were first run to determine what discrete frequencies indicative of tegules were present. TEG4A was then used for each of these suspected bands.

The objectives of the experiment were to confirm that the response from each electrode became more independent as the frequency

of the bands were increased and to determine the duration-amplitude versus frequency relationship of the tegules. Figures 5-6 through 5-12 are representative sample frames of TEG4A for the various tegule bands chosen. It should be noted that the tegule differences among the traces occur in two forms. For the lower frequency bands, the primary differences are attributable to time delays. That is, the start, stop and peak amplitude times of a tegule on one trace may lag or lead slightly those of one or more other traces. The main differences in the higher frequency bands is the frequent and complete non-coincidence of tegules from one channel to the next.

b. Analysis Results

The analysis of the experiment was performed by analysing 15% of the data frames which were picked by a random sampling technique. The duration of each of the tegules within the selected frames was measured. When the tegules displayed on the four traces differed in time, the difference was noted. Tegules that differed only in amplitude were not considered to be different since this only indicated that the peak area of cortical activity was closer to one electrode than another. The general area of cortical activity could still be common to all four electrodes.

Where coincident tegules were obviously present among the four traces, the peak amplitude of the largest tegule was measured. Since the variation in amplitudes of tegules of the four electrodes indicates the relative closeness of the electrodes to the center of peak cortical activity, then the distribution of the maximum amplitudes provides an estimate of the tegule amplitude for any band.

For each tegule band the subject was in three distinct status conditions starting with the eyes closed relaxed (ECR) then eyes open relaxed (EOR) and finally a problem status (PS). During the PS condition

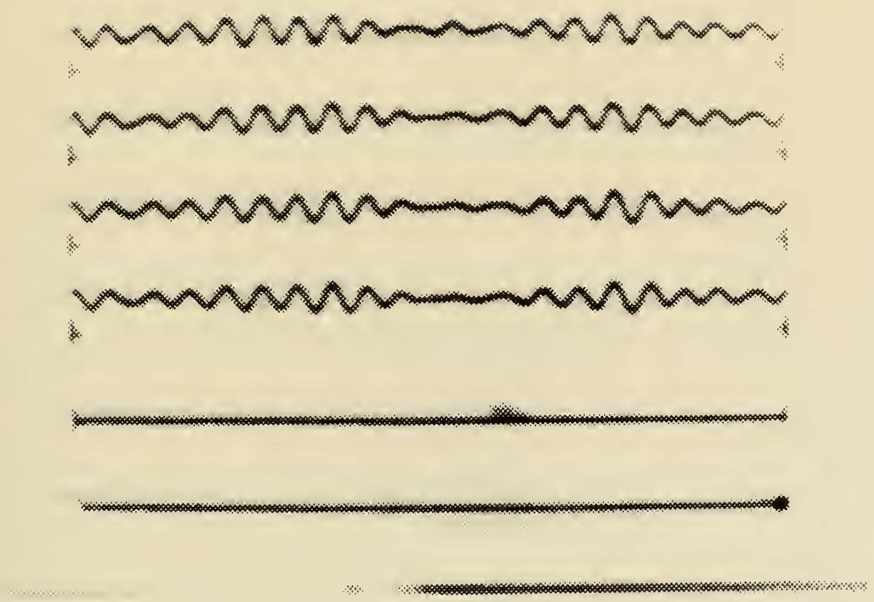


Figure 5-6. A sample frame of TEG4A from the tegule independence experiment. The band is 8-14 Hz for each trace. Note that all four traces are identical.

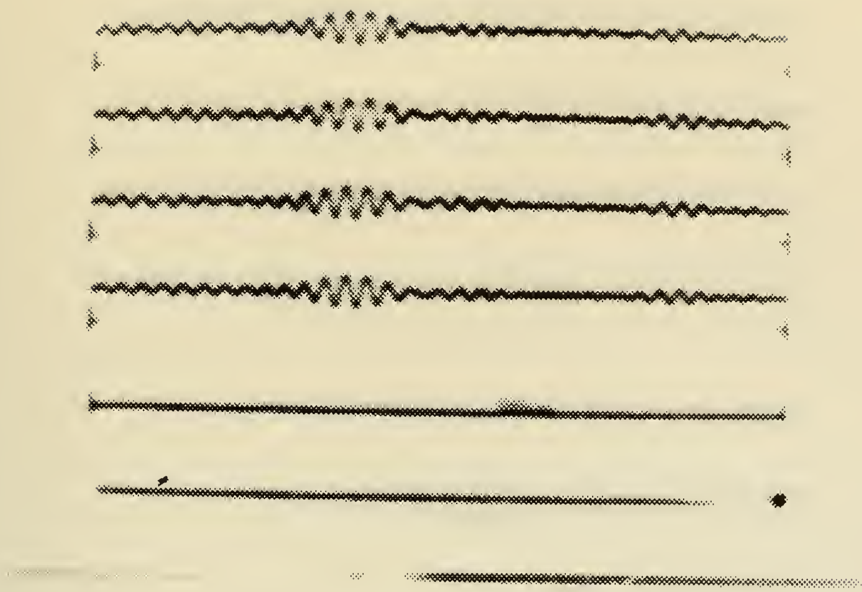


Figure 5-7. A sample frame for the tegule independence experiment. The band is 14-20 Hz. All four traces are essentially identical.

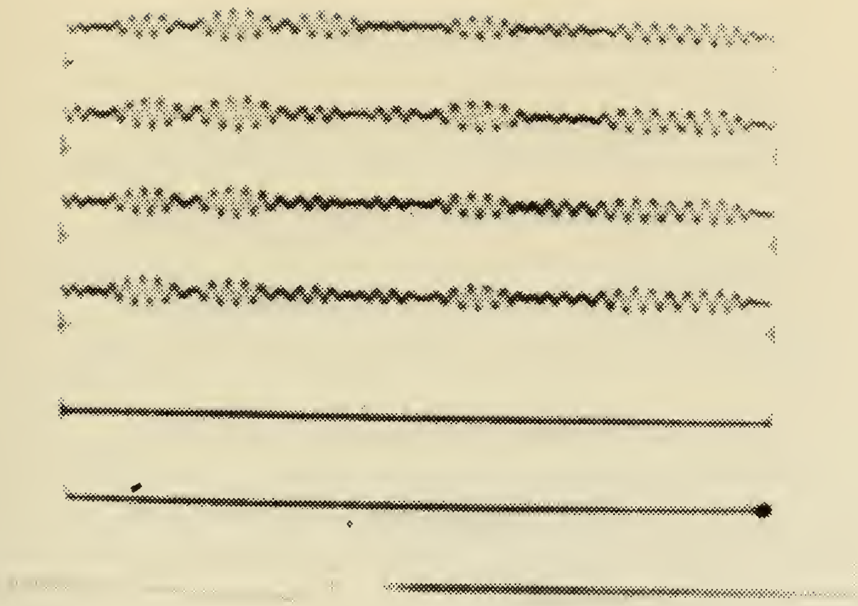


Figure 5-8. A sample frame for the tegule independence experiment. The band is 20-25 Hz. The difference for the tegule at 0.7 s in trace 1 is only one of amplitude. The tegule at 1.4 s in trace 1 is separate while a continuous large spindle is shown at the same time in trace 3. Note that two tegules close together tend to show a phase change, for example, between the first two tegules on each trace.

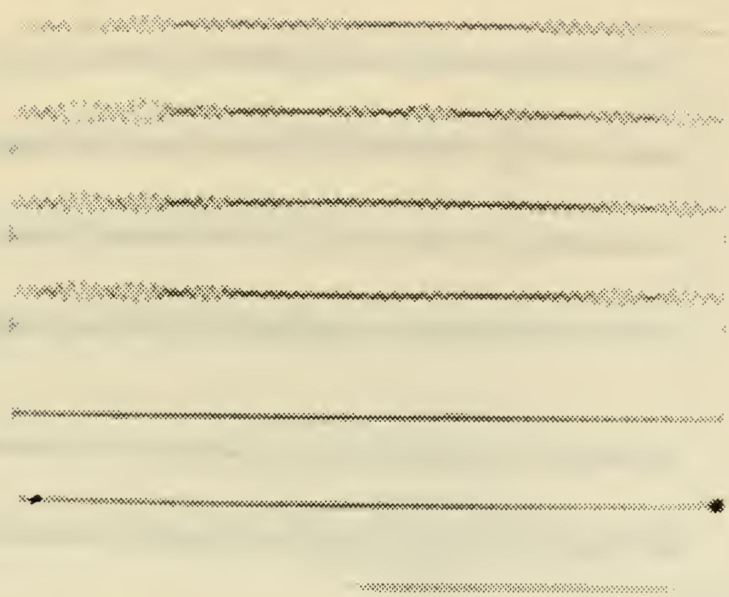


Figure 5-9. A sample frame from the tegule independence experiment. The band is 25-32 Hz. Some tegules are obviously different on different traces. For example, the tegules in traces 1 and 2 at 0.7 s differ in start and stop times.

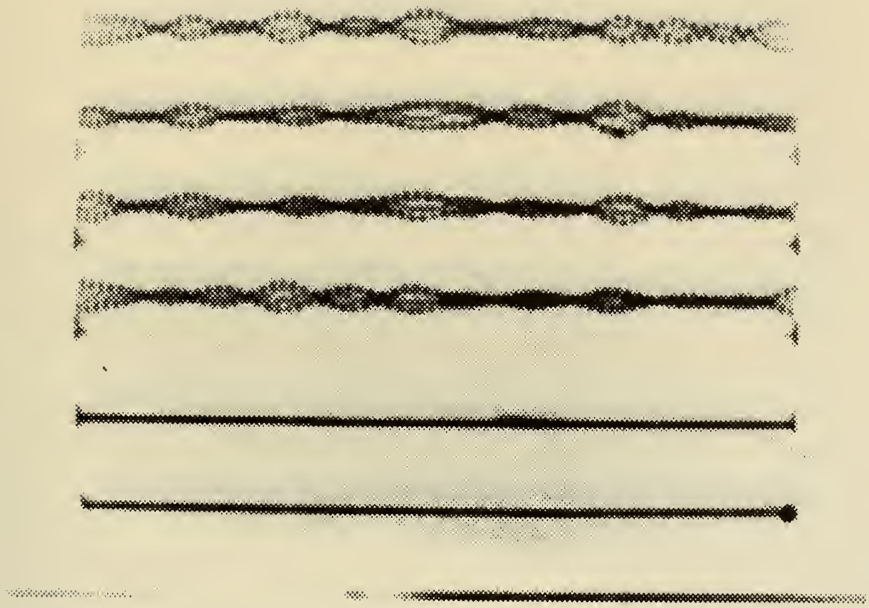


Figure 5-10. A sample frame from the tegule independence experiment. The band is 40-44 Hz. Obvious differences exist from trace to trace. At 0.8 s traces 1 and 4 appear to be the same but differ when compared with traces 2 and 3.

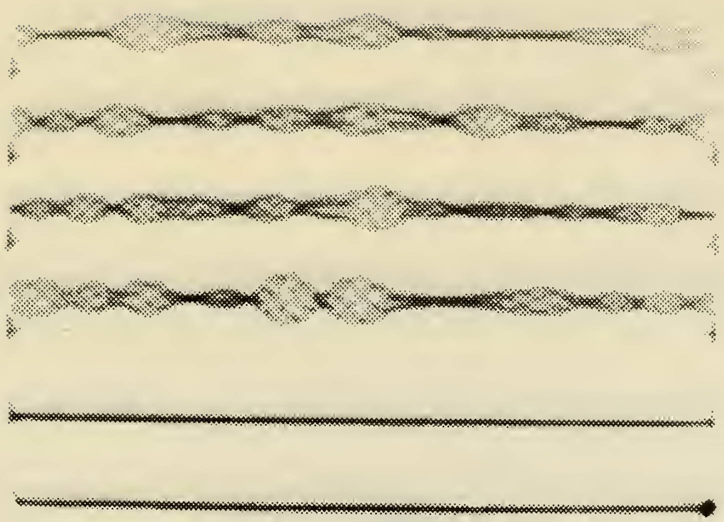


Figure 5-11. A sample frame from the tegule independence experiment. The band is 44-52 Hz. The traces differ quite obviously.

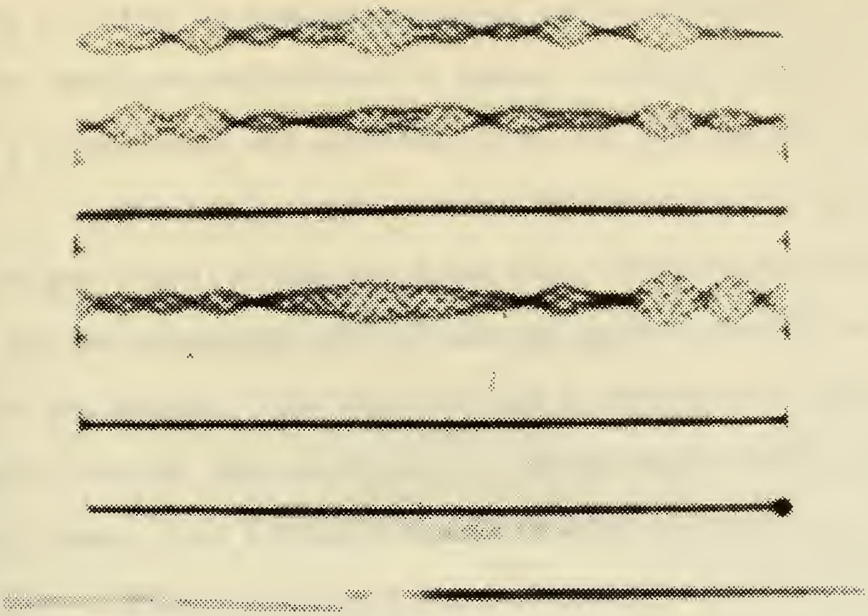
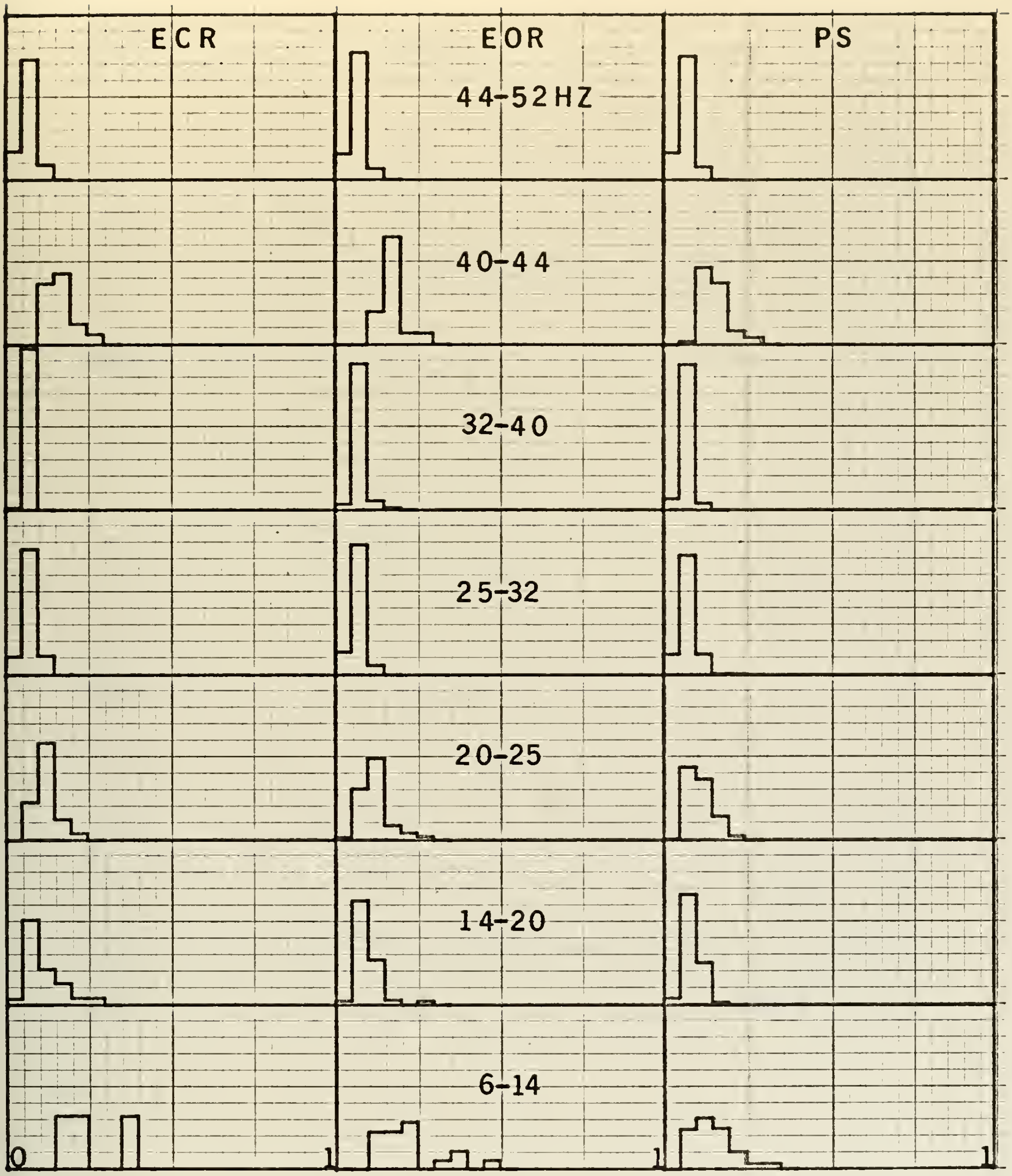


Figure 5-12. Another frame of the 44-52 Hz band from the independence experiment. Note the dramatic difference. Trace 3 is almost zero for the entire two seconds.

the subject was given a variety of problems to which he was required to obtain an answer and to indicate when a solution was obtained by pressing a button. The button activated the light described earlier. The type of problems presented to a subject varied considerably and included multiplication, division, simple algebra, calculation of square roots, solutions to quadratics, power series expressions, geometric series, antonyms and synonyms of words, a specific number of words with a given length and specified first and last letter, etc.

Further analysis was done by measuring the peak amplitude of the largest tegule within any frame for a selected electrode. Frames were chosen to coincide with 20 seconds prior to and after initiation of PS for the subject. The objective was to determine if significant variation in average peak amplitude of a given tegule band was associated with a change from a relaxed status to a PS condition for a subject.

Figure 5-13 shows the histograms of tegule duration for the subject conditions of ECR, EOR and PS for each tegule band. Results indicate that the band incorporating alpha (6-14 Hz) does not meet the definition of a tegule in that the variance of the duration is much too large. Alpha will be considered in Section VI. Observation of the data frames for the 44-52 Hz tegule band indicates that the bandwidth incorporates more than one tegule since the frequencies of the tegules vary and one tegule often starts prior to an earlier tegule even reaching peak amplitude. Figure 5-14 shows a plot of mean tegule duration and amplitude versus frequency. Figure 5-15 indicates the percentage of tegules that are different versus the frequency band. As was proposed, the results indicate that the tegules may become totally noncoincident around 50 Hz. This can only happen if the small area seen by each electrode produces 50 Hz tegules that are independent of other surrounding



Duration in seconds

Figure 5-13. Histograms of the duration of spindles for each spindle band and the three conditions of the subject: eyes closed relaxed (ECR), eyes opened relaxed (EOR) and problem status (PS). Data from a total of 1182 tegules.

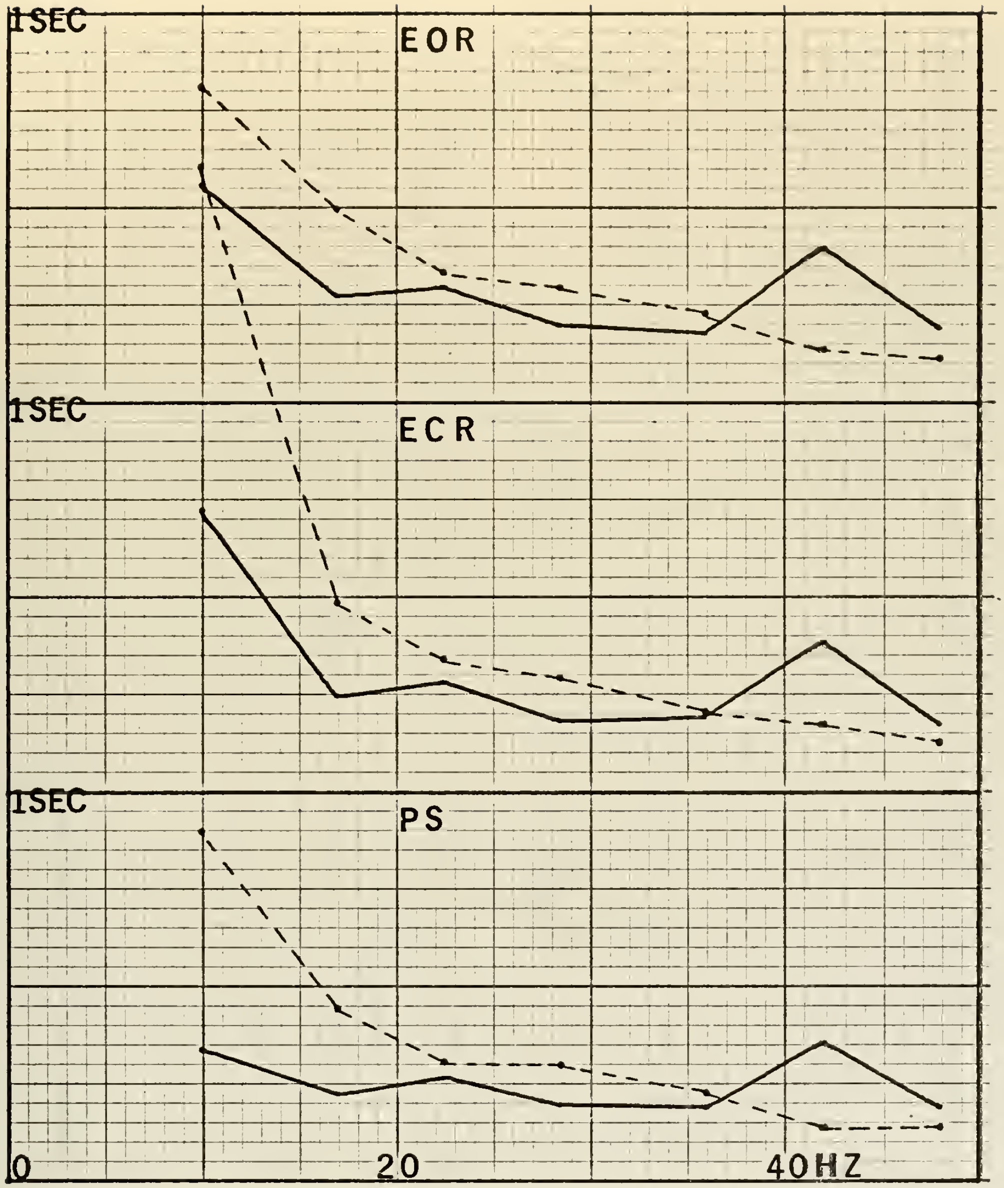


Figure 5-14. Duration (solid lines) and maximum amplitude (dashed lines) of tegules as a function of the tegule frequency. The ordinate scale for duration is 0-1 second and the scale is relative for the amplitude. The plots are the mean values in each case and represent 1182 and 617 data points for the duration and amplitude respectively.

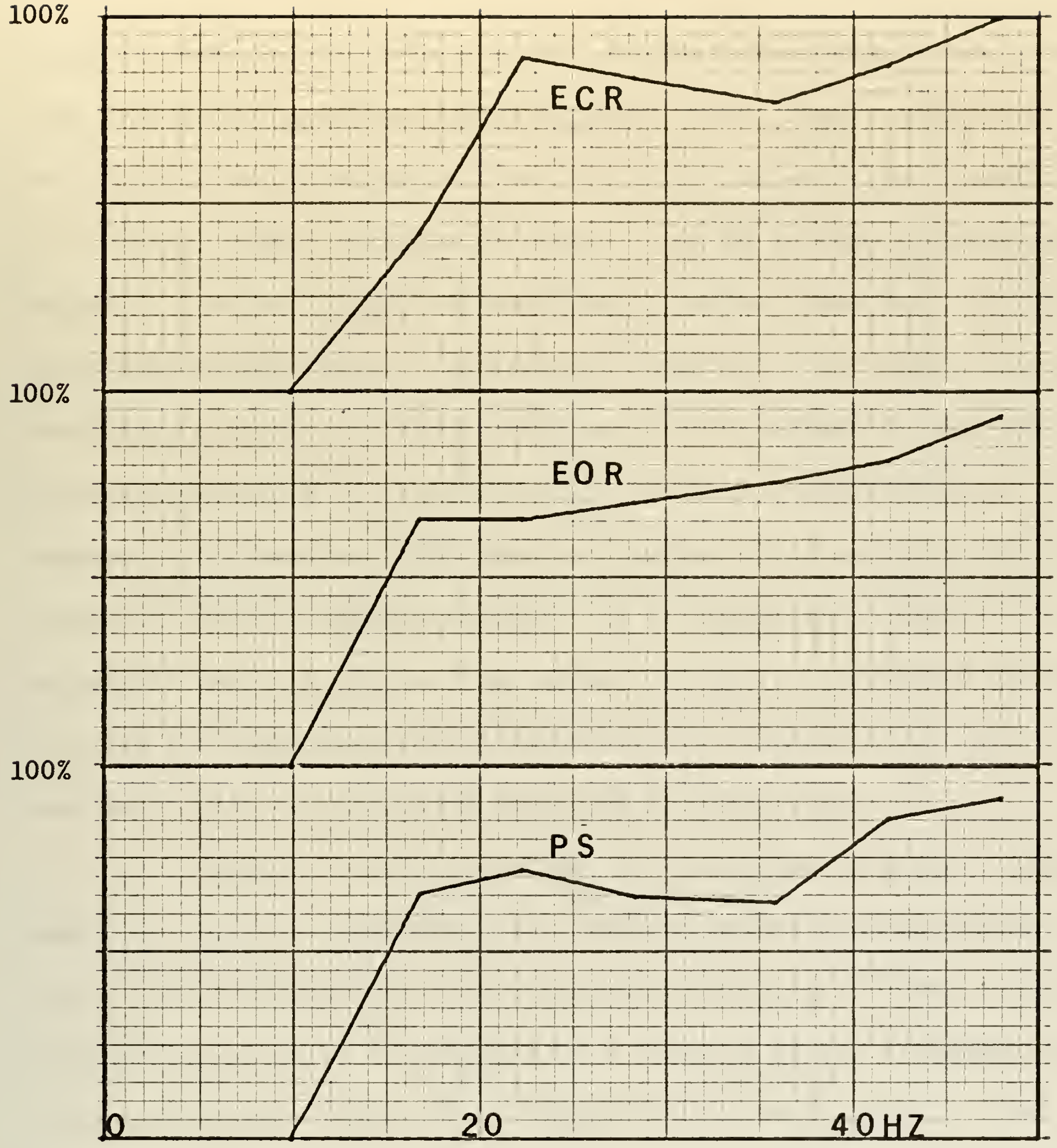


Figure 5-15. The percentage of tegules that differ from electrode to electrode as a function of the tegule frequency. Electrodes were spaced about two centimeters apart within the parietal area. Tegules were considered different if they varied significantly in time from electrode to electrode or were present on one electrode and not on another. Amplitude was not considered in determining differences.

cortical areas. It is probable that the small definable region producing high frequency tegules is only considered a unit tegule production area for a short time duration and that the area, frequency and location of the cortical region varies with time. It is as if some central controller decided a cortical region was required to process some data. The controller might then select the size and location of the cortical region according to the amount and type of data to be analysed. The result would be activation of various cortical regions somewhat similar to a computer micro program. The observed tegules would be indicative of the particular micro program activated. It is important to realize that this hypothesis does not predict that actual data will be observed as tegules but that the tegules simply indicate cortical processing of data. This hypothesis will be more fully developed in section VI.

Figure 5-16 is a plot of the histograms of maximum tegule amplitude for 20 seconds prior to a problem status (PS) subject condition and 20 seconds after PS for each tegule band. Figure 5-17 shows the mean amplitude of the tegules as a function of the frequency band for the 20 seconds prior and 20 seconds after the initiation of PS condition in a subject. The results indicate that there is no significant tegule amplitude change with subject condition.

One anomaly of the experiments requires investigation before a reasonable qualitative statement can be made about the tegule. Figure 5-14 shows the anomaly as a substantial tegule duration difference in the 42 Hz band. The mean of the 42 Hz band duration of tegules exceeded the mean of the means of the other bands by almost 2σ for each subject condition. Since alpha was not considered to be a tegule band it was not used in determining the means of the mean.

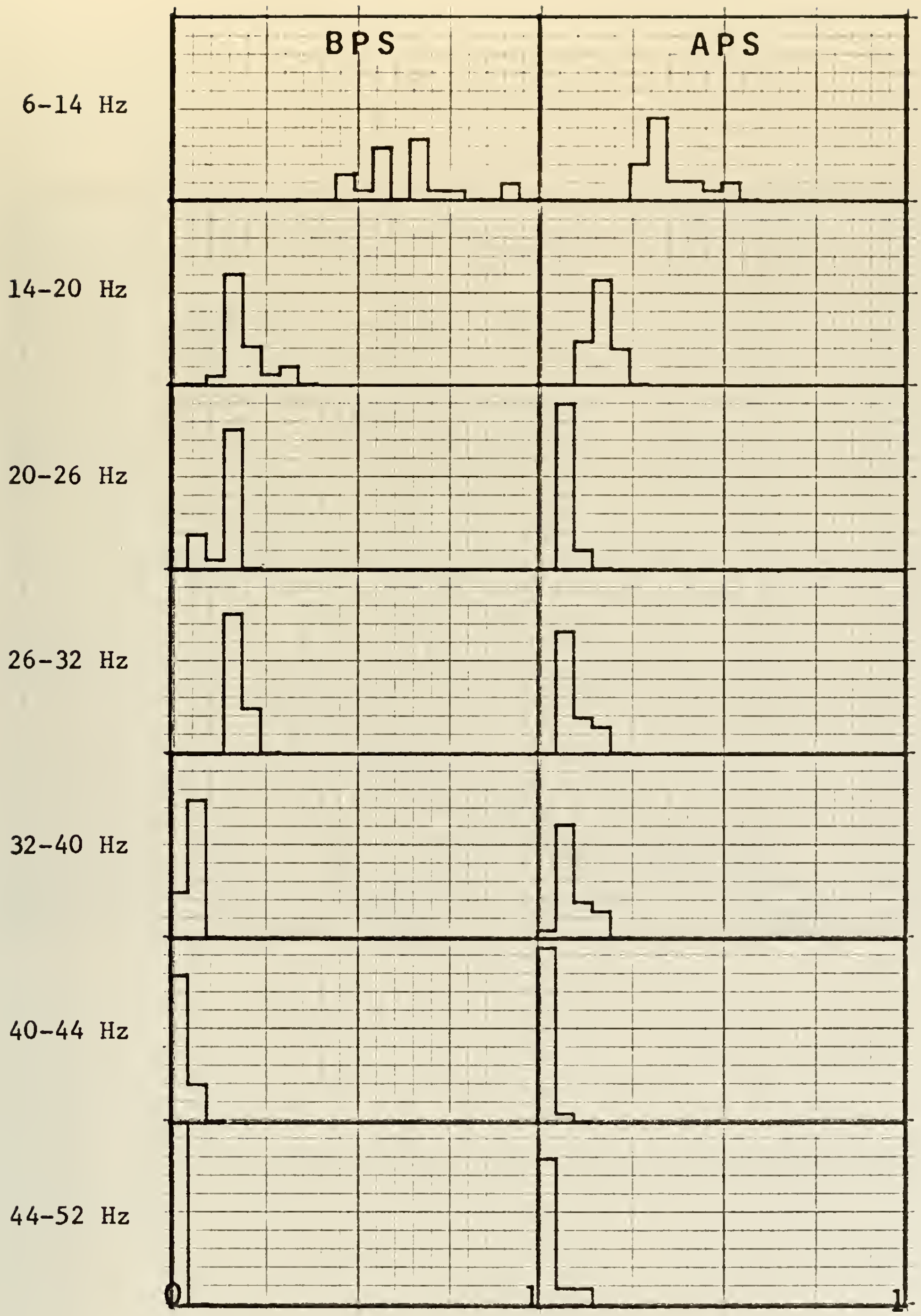


Figure 5-16. Relative amplitude histograms for the tegule bands of of the twenty seconds prior to the problem status (BPS) and for twenty seconds after the problem status (APS) is initiated. The largest amplitude tegule in each 2 s frame was used.

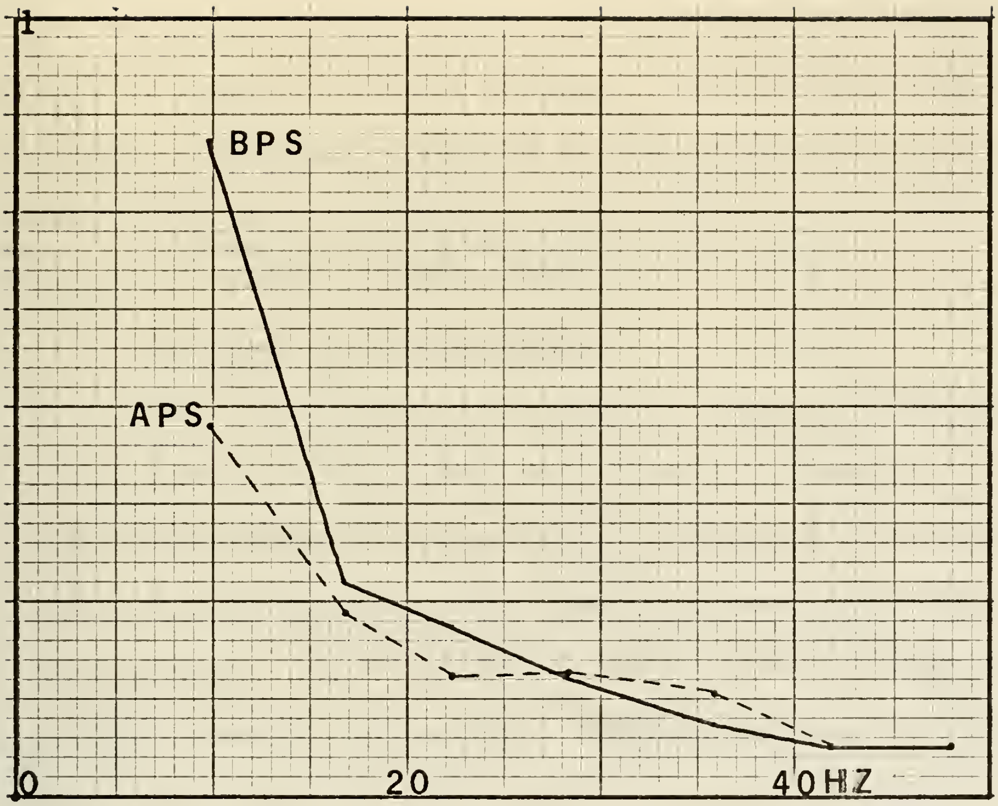


Figure 5-17. The mean value of the relative amplitude of tegules as a function of the tegule frequency. The largest amplitude tegule in each second for twenty seconds before (BPS) and twenty seconds after (APS) the subject went from an eyes open relaxed status to a problem solving status was used to obtain the data.

Definitive statements can now be made regarding a tegule. Tegules exist in bands from 14 Hz to at least 50 Hz. The bandwidth of a tegule band is on the order of 6 Hz wide. The amplitudes of tegules decrease with frequency and are not affected by a subject's mental states of relaxed or working problems. The duration of tegule is independent of frequency except for the 42 Hz band where the duration is about double that of other bands. The duration of a tegule is independent of a subject's mental state.

3. Correlated Cortical Activity

The evolving model of the brain as a parallel processor involving units of cortical area for processing information was reason to suspect correlation of various cortex areas should increase with a subject in a PS condition. The XCORR program was developed to test this hypothesis. Figure 5-18 is an example frame of XCORR for the standard electrode configuration. XCORR is based on two seconds of data and the six traces of Figure 5-18 show the cross-correlation in trace pairs with the first pair the cross-correlation of the parietal and frontal electrode; the second pair is parietal and temporal and the third pair is parietal and occipital. For each trace pair, the first trace shows τ from 0 to +2 s and the second trace shows τ from -2 s to zero.

a. XCORR Experimental Results

The XCORR experiments were done by processing 200 frames of XCORR for each tegule band. The 200 successive frames consisted of 50 frames of ECR condition, 50 frames of EOR condition and 100 frames of PS condition for the subject. Since the previous results indicated the 44-52 Hz tegule band was probably two bands, the FSEG program was first used to redefine the tegule bands. A different subject was used

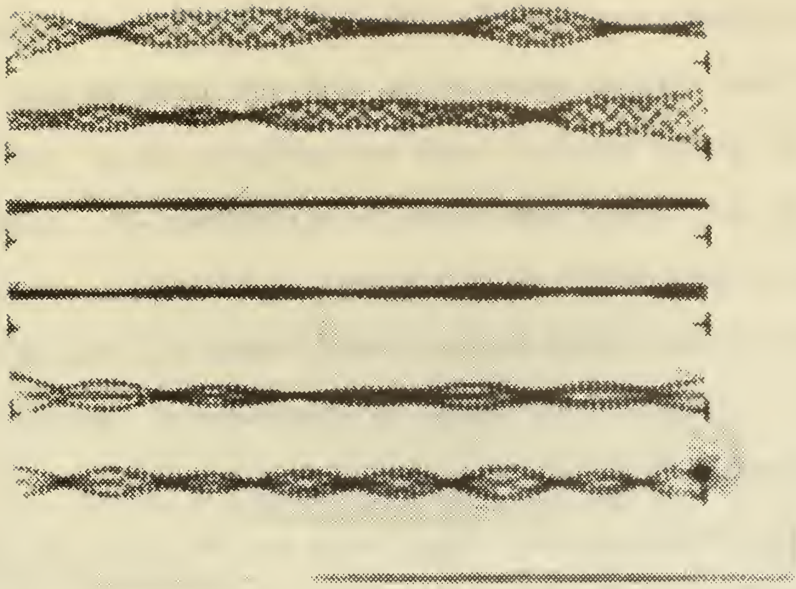


Figure 5-18. A sample frame of XCORR with standard electrode placement. The trace pairs are PT, PF, PO from the top to the bottom. Of each trace pair, the first is τ from 0 to 2 s and the second is τ from -2s to 0.

for the XCORR experiments but the tegule bands were found to be the same except that the 44-52 Hz band was indeed found to be two bands. One of the bands was 44-48 Hz and the other was 48-52 Hz.

(1) Standard Electrode Configuration. Figure 5-19 is the resultant mean values of the percentage of cross-correlation time of the parietal-frontal (PF) electrodes plotted as a function of the tegule band. A plot is shown for each of the three subject conditions; ECR, EOR, and PS. Random sampling was used to obtain 20% of the total frames for analysis. The percentage of cross-correlation time was found by measuring the percentage of time for which significant cross-correlation occurred in each 2 s frame. Each subject condition for each tegule band was treated independently to obtain the samples.

An interesting result is the small value for the EOR condition in the 42 Hz and 46 Hz bands. The anomalies associated with the 42 Hz band indicate that something very different from the rest of the bands occurs and may be significant for obtaining information about the way a subject is "thinking".

(2) Electrodes Closely Spaced. Figure 5-20 is the resultant mean values of the percentage of cross-correlation time of the closely-spaced parietal-parietal (PP) electrodes plotted as a function of the tegule band. For each of the conditions, ECR, EOR, and PS, mean values of the cross-correlation time are plotted. Random sampling techniques were used to obtain the data in the same way as the standard configuration data was obtained.

An anomaly may be present in the 42 Hz band again in that the ECR correlation time drops to a very small value.

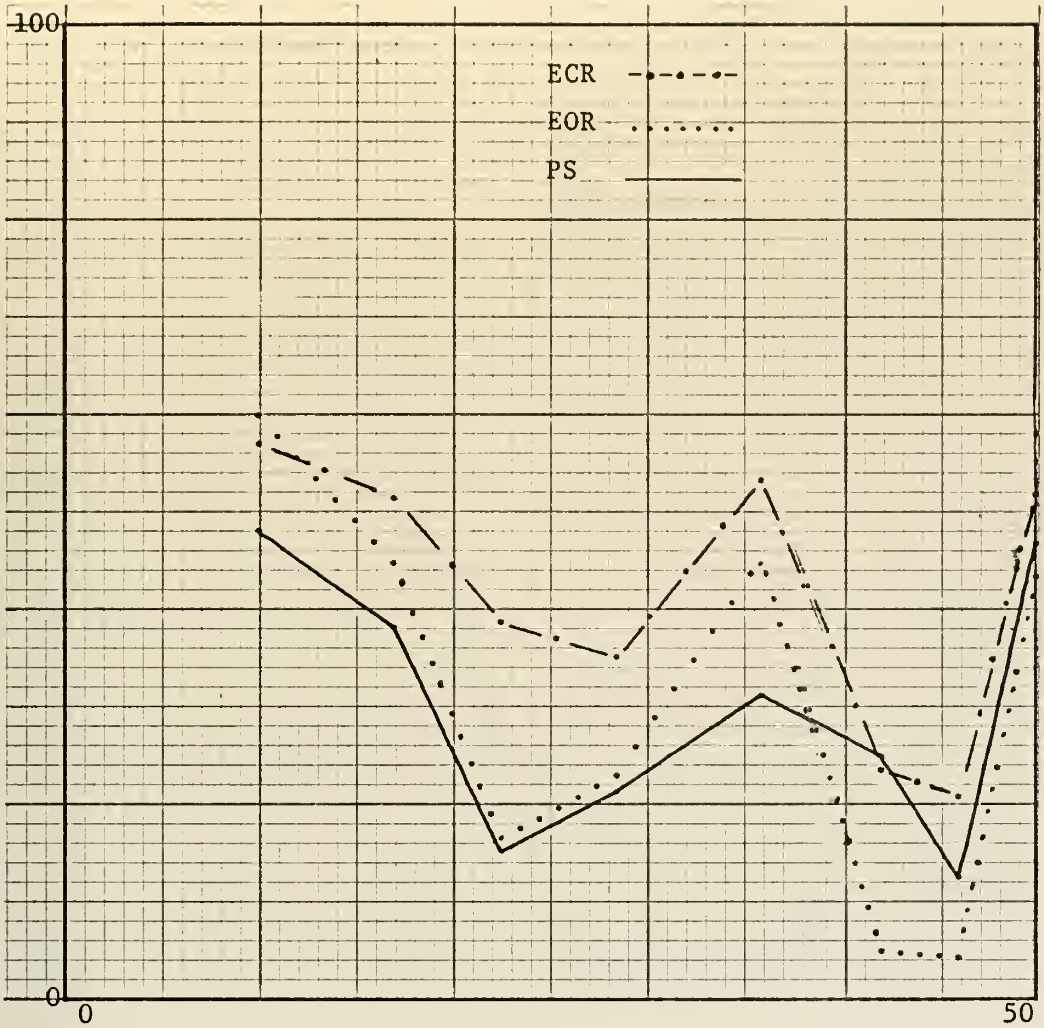


Figure 5-19. The mean value of cross-correlation time of the PF electrodes versus tegule bands. The cross-correlation time for three subject conditions is shown. Amplitude values are percentage of time during which significant correlation was present for 2 s epochs.

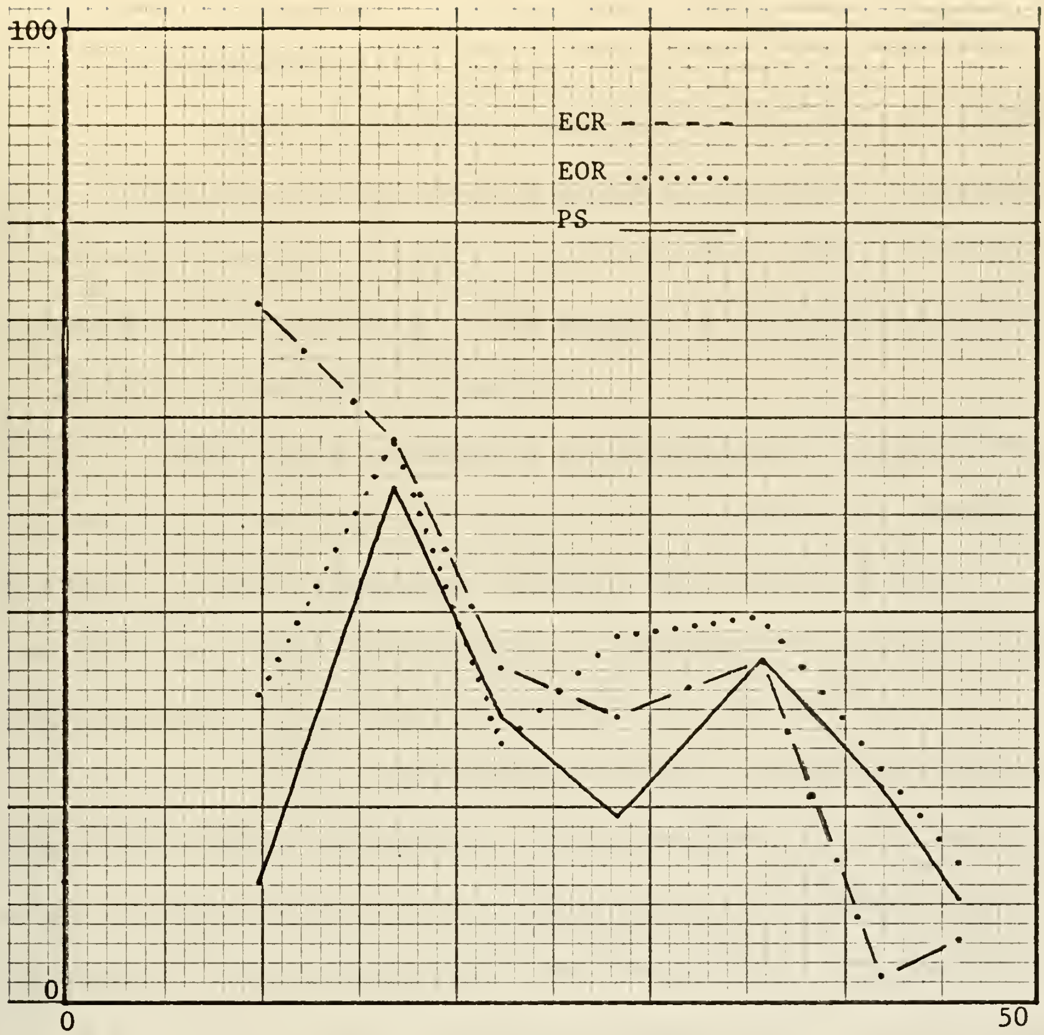


Figure 5-20. The mean values of cross-correlation time for electrodes spaced 2 cm apart at the parietal location. Three subject conditions are shown.

b. XCORR Analysis

A total of 600 frames of XCORR were analyzed as described above. Additional analysis was performed by obtaining the maximum value of cross-correlation for each 2 s epoch and determining the mean value of maximum cross-correlation. The means were then plotted as a function of tegule bands and subject condition.

When using the mean of the maximum amplitude of cross-correlation as a measurement, no significant difference was observed as a function of subject condition. However, when the percentage of time that cross-correlation was present was used as a measurement, significant differences were observed as shown in Figs. 5-19 and 5-20.

In order to show the difference in cross-correlation time between the subject relaxed and working problems, the EOR and PS mean values of cross-correlation time divided by the ECR mean value of cross-correlation time for each tegule band was plotted. The results for PF and PP electrode pairs are shown in Figures 5-21 and 5-22, respectively. The results indicate that one might determine whether a subject were working a problem or relaxing by observing the cross-correlation time for PP and PF electrode pairs. If the PP pair had large correlation time and the PF pair had a small amount of correlation time it would indicate that the subject was relaxed. A large correlation time in the PF electrodes would indicate the subject was working a problem.

Figure 5-23 is a plot of the cross-correlation time of the PP electrode pair divided by the PF pair for the EOR and PS conditions. The ratios between PS and EOR condition is about 5:1 for the 42 Hz band. It would seem then that the 42 Hz tegule band is the problem solving band. Correlation time with widely spread electrodes varies with the

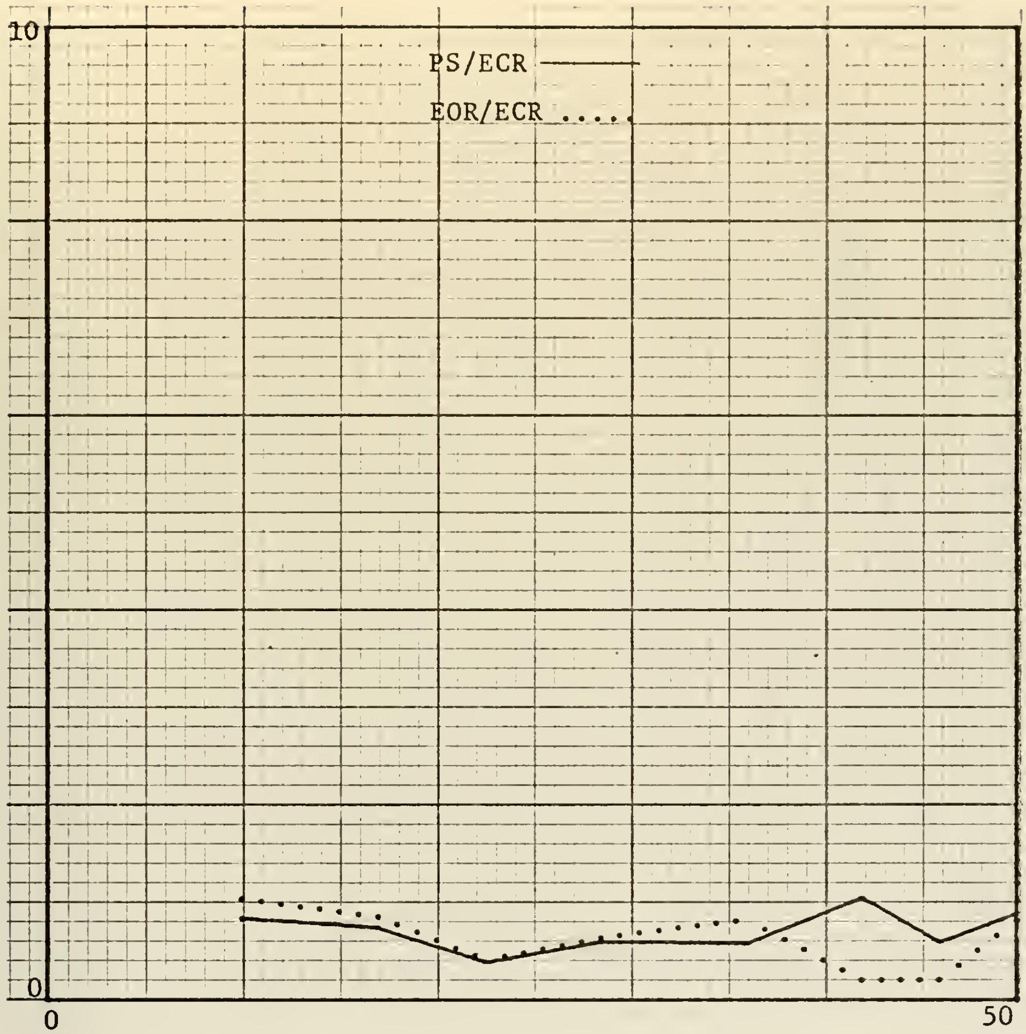


Figure 5-21. The mean value of cross-correlation time divided by the ECR subject condition for the EOR and PS conditions. Results shown are for the PF electrode pair.

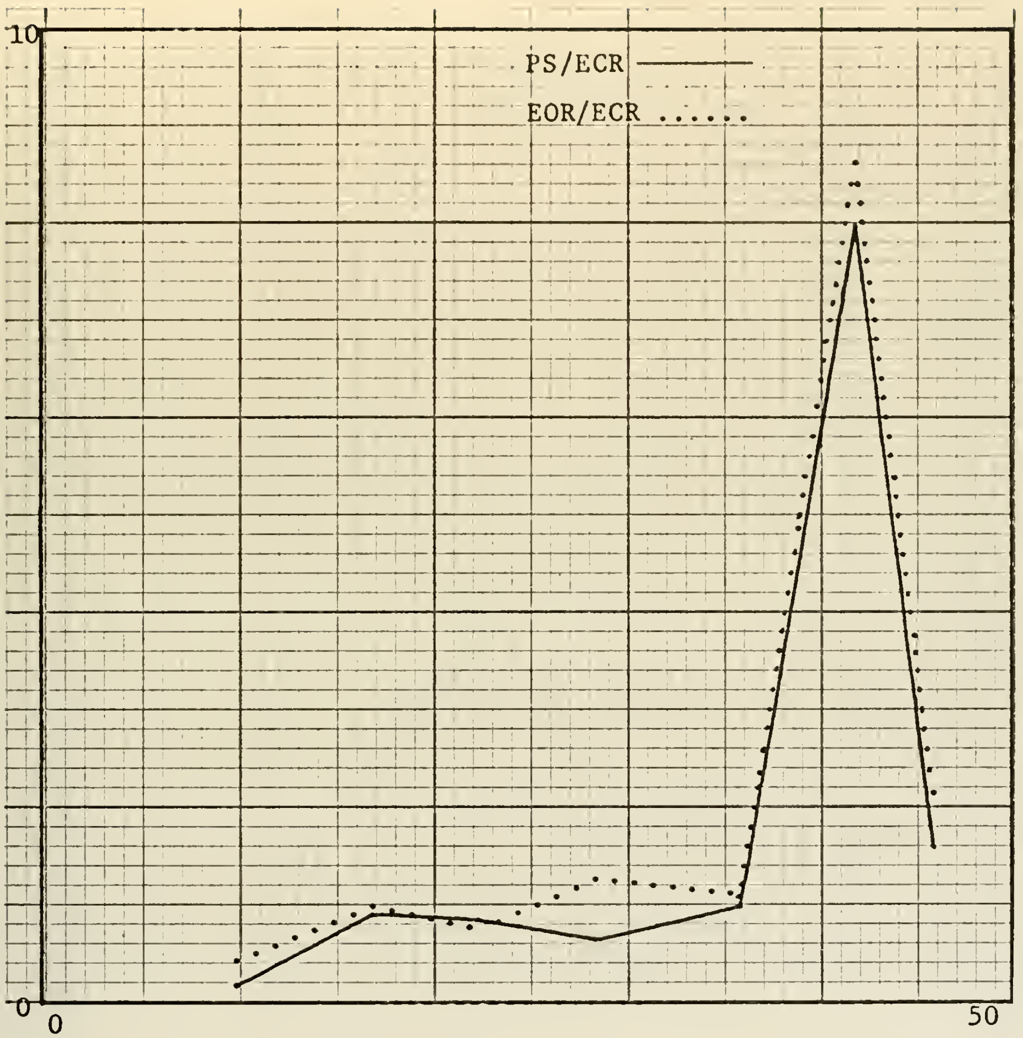


Figure 5-22. The mean value of cross-correlation time divided by the ECR subject condition for the EOR and PS conditions. Results shown are for the PP electrode pair.

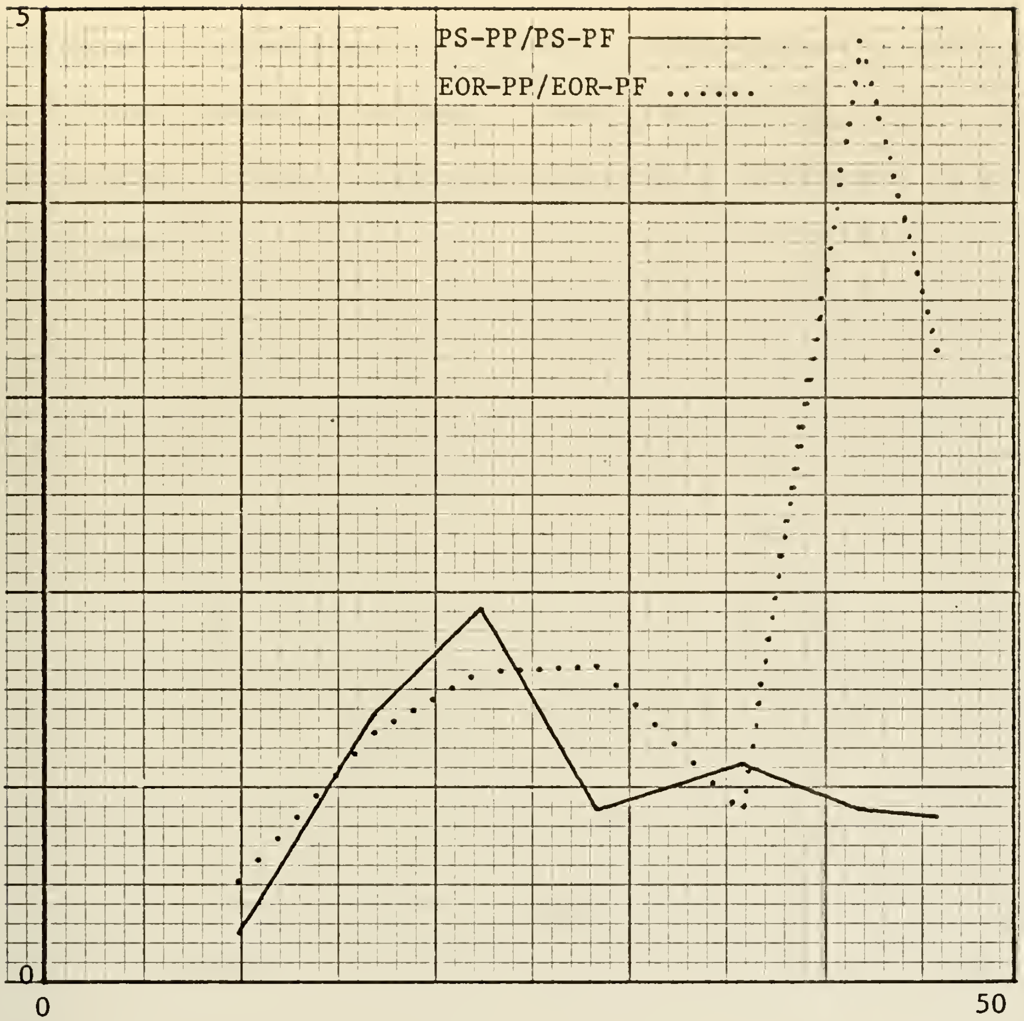


Figure 5-23. The mean value of cross-correlation time of the PP electrode pair divided by the cross-correlation time mean value of the PF electrode pair. Results are shown for both the EOR and PS conditions. The figure indicates that the cross-correlation time is much greater for close electrodes and less for far spaced electrodes when a subject is relaxed as opposed to working a problem. This would seem to indicate that widely spaced electrodes show a similar degree of correlation as the closely spaced electrodes when a subject is working a problem.

condition of the subject at 42 Hz while the variation is quite small with closely spaced electrodes. Closely spaced electrodes do show a marked change in the correlation time at 42 Hz as opposed to the other tegule bands.

VI. DISCUSSION AND CONCLUSIONS

This section is devoted to a discussion about tegules, an associative memory machine and the brain as an analog of the machine. The conclusions concerning a possible mechanism that may produce tegules is presented. This includes a further discussion of recruiting, duration of tegules and other points mentioned in Section V. The machine model is developed on the basis of an associative memory computer. The machine is shown to have the ability to remember, to learn and to think. The operation of the brain in terms of an analog of the machine is discussed. The last portion of this section suggests some areas for future research.

A. TEGULES

A significant portion of the EEG is comprised of tegules. Tegules appear to be a unit signature of cortical activity. Each tegule is considered to be the result of cortical activity indicative of data processing activity.

Before describing a mechanism for the generation of a tegule, the alpha wave should be put into perspective. The alpha wave seems to be generated by a master loop which includes specialized neural tissue in the upper brain stem and certain areas of the thalamus. This specialized tissue is known as the reticular activating system (RAS). If the RAS is not functioning, no alpha waves are generated [Ref. 14]. When an individual is asleep the alpha waves disappear; they are an accompaniment of the waking state.

Volleys of nerve impulses generated by the RAS and repeated every .1 s and then transmitted in parallel by very large numbers of nerve

fibers throughout the nervous system may thus be considered a clocking signal. The cortex continually receives these impulses as one of its inputs during the waking state. This results in an undulating sub-threshold potential (the alpha wave) in certain important cells in the cortex such as pyramidal cells. Therefore, these pyramidal cells will be more readily excited by other inputs, such as from local neurons, which are coincident with the trough of the membrane potential of the pyramidal cells produced by the incoming volleys at the alpha frequency. Since the alpha input will affect millions of cells, it will serve as a general synchronizer of brain activity.

Thus a local initiating input to a given pyramidal cell will be more apt to fire the cell when that input is in coincidence with the alpha trough. If the output from the pyramidal cell excites a local reverberating circuit consisting of a ring of neurons, each exciting the next, then a local synchronizing frequency will be setup. This local frequency may be assumed to be higher than the alpha frequency. The outputs from the reverberating circuit may then be fed back to the initiating neurons tending to synchronize them to the frequency of the reverberating circuit.

This type of mechanism could give rise to the tegule. The result would meet two of the defining requirements for a tegule. It would have a discrete frequency and would be locally generated. In addition, the resulting potential fluctuation would tend to increase in magnitude as more loops were recruited. A modest increase in frequency might be expected as loop transmission was facilitated.

One may suppose that the tegule might be terminated due to one or more of the following possibilities. First, fatigue may occur. Secondly, the processing sequence, of which the tegule is a sign, may reach its

conclusion. The conclusion of the process would result in an output from the processing area to other parts of the brain. It would be expected then that the local process would be terminated by inhibition of the reverberating circuit. The output itself may be fed to the reverberating circuit as an inhibitory signal thus establishing a self extinguishing processing system. The initiation of higher priority processing may also interrupt a reverberating circuit via inhibitory inputs to the circuit. The experimental fact that the tegule's duration does not appear to be a function of the frequency is not inconsistent with the latter two methods of termination. If fatigue were the only method of termination, then one would expect the duration of tegules to decrease with frequency.

The generation of the alpha waveform by a master loop incorporating the RAS as a very important element now has strong experimental support from the results of many researchers. It is generally accepted by neurophysiologists. The explanation of how this clocking waveform (the alpha) may give rise to higher frequency synchronizing trains of pulses, as given above, is certainly consistent with present knowledge. It depends upon the concept of the reverberating circuit. This concept is supported by a large amount of indirect evidence from studies of various types of neural mechanisms, such as sensory processing and muscular servo control type of processing. What is new here is the identification of the tegule as an important part of the scheme of cortical local processing.

B. A POSSIBLE MODEL OF THE BRAIN

1. A Parallel Processor

The analogy between the brain and a computer has been proposed many times. The application of the analogy is really quite naive but

may be useful for some purposes. If the analogy is to be used, there are distinct differences which must be recognised. A digital computer is basically a serial processing machine which can perform individual instructions in less than a microsecond. Therefore, the computer can perform arithmetic operations very fast. If the synaptic input causing a cell to reach the threshold for producing an action potential and the effect of the resultant action potential on the next synapse in series is considered an individual instruction, then the speed of the brain is much less than a computer. The largest amount of the time required for the propagation of an action potential in cortical circuits is due to synaptic delay. The delay is the result of the discharge of the chemical transmitter by the synaptic knob, the diffusion of the transmitter across the synaptic cleft and the action of the transmitter on the receiving dendrite. This process typically requires 0.5 ms or longer. Thus, the basic speed of the brain is at least three orders of magnitude less than that possible of computers.

Arithmetic operations are serial by nature and a computer performs much faster than a man on this type of problem. However, a computer cannot even accomplish many processes that a man performs quite accurately and quickly. For example, a man can recognise one face in many thousands almost instantly. He can recognize a voice on a telephone after a single word. Since the individual process speeds of a man are slower than a computer then the only way to account for man's ability is via some sort of vast parallel processing mechanism.

With 10^{10} neurons available in the cortex alone, there are sufficient devices present to allow for many levels of parallel processing and a tremendous amount of redundancy. The actual mechanism by which data is processed in the brain is unknown.

2. A Model for Thinking

Thinking will be defined as the processing of data such that new associations are formed. It now becomes necessary to propose a mechanism by which thinking could be done. A possible mechanism in the form of a machine model will be shown. Then an analogous possibility within the brain will be shown.

a. The Machine Model of the Brain

Consider a machine with a virtually unlimited amount of memory. Assume that each memory word can have any required length. The memory is a programmable microcode (PMC) and originally contains a few basic instructions such as add, multiply, move, etc. Thus, the PMC would connect as many types of processors and/or other memories as necessary to complete an instruction. A PMC is accessed by any portion of an instruction code exactly matching a specific PMC. A match for any PMC would inhibit the output of all other PMCs of lower priority. A series of instructions just performed would be stored as the code for another PMC and the location of the result of the process would be stored as the output of the PMC. The stored result would decay exponentially as a function of time. There is a threshold such that if a process were repeated often enough over a short enough time span, the PMC would no longer be volatile.

The machine would have the capability of learning and thinking and remembering. As an example, the machine may be given the command 'A+B= ?' with the correct answer being 'C'. The A and B would be sent directly to processors and would await a processing command. Since all PMCs are accessed simultaneously, the PMC with the stored code for '+' will be accessed immediately and would be the only one with an output.

The output commands the processor to add. The output of the processor is made available to the user. The final operation is the storage of the code 'A+B= ?' as the address of a different PMC and to store the location of C as its output. The priority of this PMC is now one higher than the PMC holding the code for add. Assume that the same instruction/question were put to the machine a short time later. The PMC holding the command add and the PMC holding the command 'A+B= ?' will both be activated but, the latter would inhibit further processing of the add PMC and would report the result C with no processor action required. The final action would restore the command and result location to the 'A+B= ?' PMC. Thus the machine has remembered an answer obtained previously.

Assume an optical input were available and the machine was shown a vertical line. The coding representing the direction of the line would be stored in one PMC and the length code in another. The line is shown a number of times such that the associated memories are no longer volatile. The identification of the object as a vertical line is also stored. The same could be done for a horizontal line. This process is continued for a set of such lines. Now the machine is shown a square made up of lines from the previous set. The processing would consist of the simultaneous activation of the four PMCs associated with the four lines of the square (parallel processing) which would then activate a new PMC for the storage of the associated data from the processed square. The machine has learned that a square is made up of two vertical and two horizontal lines. It should be noted that the processing did not involve a processor but was the orderly routing of signals through the memory based on the results of comparisons with previously stored data. A

machine of this type would be capable of performing pattern recognition on extremely complex data (such as a human face) in essentially the same time required to perform a single arithmetic operation.

The above described machine requires some additional features. The entire memory could never be accessed simultaneously since this would require an inconceivably large number of input lines. But, the memory might be divided into sections. Each section of the memory would be activated at a specific voltage level different from the level for any other area. The activating voltage for the memory area would be varied as a function of time. This clocking of memory area activation would interrupt when an activated area had data to be processed until the area no longer required the data.

The complex associations that could be remembered as a result of machine usage would result in many sections of memory having various associations of the same data forms. Each section of memory has a certain probability of being activated at any given time, and the particular section of memory active when data was inputted could not be predicted. Thus, the specific associations for the data could not be predicted. But this means the exact processing could not be predicted nor could the exact answer. The machine is a stochastic computer.

The machine naturally suffers from incompleteness and infeasibility. It also suffers the complete lack of self awareness.

b. <u>The Brain as an Analog of the Model</u>

Virtually nothing is known about the process of memory in the brain. It has been said to be distributed throughout the cortex. It has been proposed that a specific path involving many neurons traversed by a signal alters the neurons involved. The alteration is such

as to make the path more easily traversed by the same type of signal in the future. The more times a particular path were traversed the more it would modify the neurons to accept only the original type of signal.

The act of remembering might be defined as the comparison of stored events (memories) with data requests until the desired result is obtained. The nature of the data request is such that some form of clue (code) to the desired result is included. This would imply that parameters of a memory would be stored together. For example, assume three parameters associated with people were stored. The parameters might be face, voice, name. If that person were met, a data request for memory might be of the form, compare faces and voices until a match with incoming data is found and return the associated name. The clues would be voice and face.

The comparison search might be accomplished by reverberating circuits. The data for which a match is desired would be circulated continuously and the data to be matched would be fed in parallel to a comparator. An output of the comparator would result only for a complete data match.

3. Thinking

Thinking cannot be completely separated from remembering or associating. Indeed, thinking is really the association of ideas, concepts, situations, etc., in such a way as to try to make new or different associations. No concise definition can yet be made for thinking or any other mental process. Any definition proposed will either be so simple and incomplete that it only covers a very limited portion of the general process or so all inclusive as to have little meaning. This is a result

of the extreme complexity of the brain and its processes. Thus, the term thinking will be limited to the simple definition proposed in part 2 and only the very basic example of the square used for the machine will be covered.

Research has established that the occipital region is one of the areas where visual processing takes place. There are areas in the occipital region where lines observed by the eye are mapped. The mapping seems to be one for one as to length, orientation and position. Assume a naive child is shown a large set of vertical and horizontal lines and that the lines are identified. The lines would be laid down as memories and their parameters would be associated. The demonstration is repeated until the memory paths have been traversed often enough to ensure memorization. The child is then shown a square made up of lines from the set he has memorized. The lines in the square would map to the same area of the occipital region as some of the previously memorized lines. The mapping information for the square would be stored as memory and associated with the name 'square'. But, the associations with the line responses would also be stored. Given enough squares, the child would deduce that all squares he had seen were made up of vertical and horizontal lines. Obviously the process would be very similar to the way the machine model 'thought'. Thought has again occurred as the result of the orderly routing of signals through memory based on the result of comparisons.

C. FUTURE RESEARCH EFFORTS

1. A Possible Feedback Source

One of the most important objectives for future research is to determine types of EEG activity which, after processing, could be used as feedback reinforcement of the subject.

The author strongly feels that the peculiarities observed in the 42 Hz tegule band warrant further investigation. There appears to be a definite relationship between thinking and cross-correlations with different areas of the brain at this frequency. It is suggested that the future work take the form of determining which areas used for cross-correlation result in the most significant differences when a subject is thinking as opposed to relaxing. Then the amount of consistency from subject to subject should be determined.

The requirements of an effective feedback signal are (1) that it contain only relevant signatures indicative of the effective task performance and (2) that it should not distract the subject from his task. The objective desired is that the subject come to associate certain patterns with past effective performance for a given task. For feedback of simple signatures it is suggested that the feedback signal to the subject take the form of a general background illumination color for the equipment on which the task is presented. The illumination scheme is suggested as a convenient method of providing feedback without complex circuitry requirements.

Multiple feedback signals will vary and the subject may require knowledge of these patterns in order to influence his mental processing. Therefore, a simple illumination may no longer be sufficient. The obvious solution is a feedback signal presented in a format such that the subject can readily identify patterns associated with effective thinking. A reflected image from a polar display oscilloscope might be an effective medium for the feedback signal presentation.

2. <u>HUD</u>

The bioengineering team has an aircraft HUD system available. The integration of the HUD into the research equipment as a display

vehicle is an exciting possibility. The HUD might be used as the medium for presenting feedback to a subject. This would be applicable to many tasking situations, including pilot simulation tasking. It is suggested that the integration of the HUD into the signal analysis system be the basis for a master's thesis.

3. Continued Analysis Effort

A large amount of work is still required for the analysis of the EEG. Hopefully, the final result will be to establish definite meaning to the signals comprising the EEG.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The first series of results of a major research project for the analysis of the electroencephalogram (EEG) are reported.

The requirements of a system capable of real time, multidimensional analysis of the EEG are described. The time and frequency domain computer analysis programs written for the project are discussed.

A major result of the research indicates that a significant portion of the EEG is composed of a series of discrete frequency sinusoids. These

signals have a spindle shape and their average durations are constant over the frequency range from 14 to 50 Hz, with the exception of sinusoids of 42 Hz. The signals are defined as tegules.

The properties of a tegule are defined, as found from experimental results.

The anomaly with respect to the 42 Hz tegule is related to the subject's mental state and may be a source of feedback to indicate whether he is thinking or relaxing.